

# The Energy System Ontology: A conceptual framework for energy transition research

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## HIGHLIGHTS

- The Energy System Ontology (ESO) is a conceptual model of five interconnected dimensions of the energy transition.
- Corpus-informed terminology is refined through expert assessment and collective review.
- Eighteen ontology design patterns formalize cross-domain energy-system relations.
- ESO has been applied as a semantic resource in an empirical research workflow.

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## ABSTRACT

The energy transition is characterized by the increasing complexity and interdependence of technological, economic, policy, environmental, and social dimensions. While a large and rapidly growing body of literature addresses these aspects, differences in terminology, conceptual scope, and analytical focus hinder the integration of findings across studies and the alignment of diverse modeling approaches. This paper presents the Energy System Ontology (ESO), a comprehensive conceptual framework developed to bridge these gaps and support the structured organization and synthesis of knowledge related to energy systems and energy transition. ESO is constructed through a systematic, multidisciplinary review of the energy transition literature combined with ontology engineering principles to ensure robustness. The framework identifies and formalizes core relationships across energy technologies, markets, policies, and environmental contexts, enabling a consistent representation of the energy nexus while preserving vital disciplinary distinctions. The resulting ontology provides a domain-wide reference that supports comparative analysis, semantic interoperability across heterogeneous energy-system representations, and the systematic exploration of transition pathways. The current evaluation provides requirements-based verification and application-oriented evidence rather than independent external validation. By offering an explicit and extensible structure, ESO contributes to greater transparency and provides a robust framework for the analysis of socio-technical systems within the energy transition.

## 1. Introduction

There is no single, universally accepted definition of energy transition, as the concept has progressively evolved in response to changes

in energy sources, technological developments, institutional settings, and societal priorities. While the Intergovernmental Panel on Climate Change (IPCC) broadly defines transition as a process of change from one

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## Abbreviations

|        |                                                               |            |                                                                                              |
|--------|---------------------------------------------------------------|------------|----------------------------------------------------------------------------------------------|
| AI     | Artificial Intelligence                                       | NGO        | Non-Governmental Organization                                                                |
| BAU    | Business-As-Usual                                             | ODP        | Ontology Design Pattern                                                                      |
| BFO    | Basic Formal Ontology                                         | OEO        | Open Energy Ontology                                                                         |
| CGMES  | Common Grid Model Exchange Standard                           | OGC        | Open Geospatial Consortium                                                                   |
| CIM    | Common Information Model                                      | OWL        | Web Ontology Language                                                                        |
| DEHEMS | Digital Environment Home Energy Management System             | RDF        | Resource Description Framework                                                               |
| DOLCE  | Descriptive Ontology for Linguistic and Cognitive Engineering | SAREF      | Smart Appliances REFERENCE                                                                   |
| EKG    | Energy Knowledge Graph                                        | SAREF4ENER | SAREF extension for the energy domain                                                        |
| EREON  | ETS-Related European Ontology                                 | SCO        | Smart City Ontology                                                                          |
| ESO    | Energy System Ontology                                        | SDC        | Sustainable Development and Climate                                                          |
| ETS    | Emissions Trading System                                      | SDG        | Sustainable Development Goal                                                                 |
| EU     | European Union                                                | SPARQL     | SPARQL Protocol and RDF Query Language                                                       |
| GDP    | Gross Domestic Product                                        | SUMO       | Suggested Upper Merged Ontology                                                              |
| ILO    | International Labour Organization                             | TERMINUS   | (TERRitorial Management and Infrastructures ontology for institutional and industrial Usage) |
| IPCC   | Intergovernmental Panel on Climate Change                     | UFO        | Unified Foundational Ontology                                                                |
| LLM    | Large Language Model                                          | UML        | Unified Modeling Language                                                                    |
|        |                                                               | W3C        | World Wide Web Consortium                                                                    |
|        |                                                               | WGS84      | World Geodetic System 1984                                                                   |

state to another, in practice the term encompasses technological substitution, market restructuring, policy reform, and wider socio-ecological transformation [1]. Today, energy transition commonly refers to the shift from fossil-based energy systems towards predominantly renewable and more energy-efficient configurations. Within this broader debate, increasing attention has been devoted to the social implications of transition processes. The notion of “just transition” originated in the labour movement to protect workers affected by environmental and structural economic change [2]. It was later institutionalized by the International Labour Organization (ILO) [3], and has since been incorporated into climate and energy policy discourse, emphasizing equity, fairness, and distributional impacts. Beyond definitional debates, energy transition is widely recognized as a multidimensional and systemic process that spans technological infrastructures, market arrangements, governance structures, and social practices. The interdependencies among these dimensions generate coordination challenges and feedback effects that cannot be adequately captured through sector-specific or purely technical perspectives. Addressing such complexity requires conceptual frameworks capable of integrating environmental, strategic, policy, behavioral, and operational aspects within a coherent analytical structure.

The objective of this paper is to establish a common reference that maps the multidimensional nexus between technology, policy, society, and the environment. To this end, we propose the Energy System Ontology (ESO) to shed light on the inherent multidisciplinary and interdisciplinarity of energy transition. According to Gruber [4] and Borst [5], an ontology is an explicit, formal specification of a shared conceptualization. Indeed, it is a conceptual model of a fragment of an observed reality gathering interlinked concepts pertaining to a given application domain [6]. Beyond mere classification, ESO is designed to formalize how technological deployments and social practices, driven by specific policy frameworks, interact with and impact environmental constraints. By integrating environmental parameters (such as resource depletion or emissions) with socio-technical dynamics, the ontology enables a holistic evaluation of transition pathways, ensuring that sustainability is not a separate layer but a fundamental component of the energy system’s structural logic.

From a practical perspective, a multidisciplinary ontology of the energy system can support semantic interoperability by providing explicit concepts and relationships across technological, economic, policy, environmental, and social domains. ESO is not intended to reproduce the internal schema of individual energy models or industrial standards. Rather, it provides a reusable semantic layer through which

heterogeneous representations can be interpreted, related, and, where appropriate, mapped to common domain structures. Such mappings may involve direct correspondences between concepts or structural correspondences in which the meaning of an external element is represented through a combination of ESO classes, relations, and ontology design patterns (ODPs). An ontology design pattern is a reusable and structured modeling solution, designed to capture common relationships and concepts, facilitating the development of ontologies [6,7]. This capability provides a semantic basis for the integration and comparison of heterogeneous energy-system knowledge while preserving the specific modeling assumptions and structures of the original resources.

Energy transition spans technological, economic, institutional, and social domains, requiring coherent semantic integration across heterogeneous data and models. Ontologies provide semantic infrastructures by defining explicit concepts and relationships and can thereby support interoperability between technical and socio-economic knowledge bases. More generally, formal semantic resources such as ontologies and knowledge graphs are increasingly investigated as external knowledge structures for large language model (LLM)-based systems. Previous studies show that knowledge-graph-based grounding can support the integration of external knowledge, mitigate hallucinations, and improve inference and transparency in LLM-based applications [8–10]. By making domain terminology, relations, and modeling assumptions explicit and machine-readable, ontologies can therefore provide structured semantic context for such systems. This general observation motivates a potential future use of ESO as a domain-specific semantic resource for LLM-based energy applications; however, the present study does not evaluate an ESO-grounded LLM or claim improvements in LLM performance.

This relational way of thinking about energy and its transition is close to thinking about it in terms of social practice theory, which focuses on behaviors not as related to individual mental processes, but rather in terms of routine actions, material elements, bodily actions, and meanings within a social context [11]. Social practice theory can provide “useful heuristics that link different domains of reality, and this can enable parameters of physics to be quantified in novel ways and, importantly, with a human face” [11]. As Shove and Walker wrote, referring to Theodor Schatzki, “accounting for change is not a matter of abstracting sets of forces or systems (e.g., of technology, economics, politics, etc.) but of detailing precisely how social practices, and bundles and constellations of practice, hang together, and of identifying the material and other arrangements amidst which they transpire, and which they also

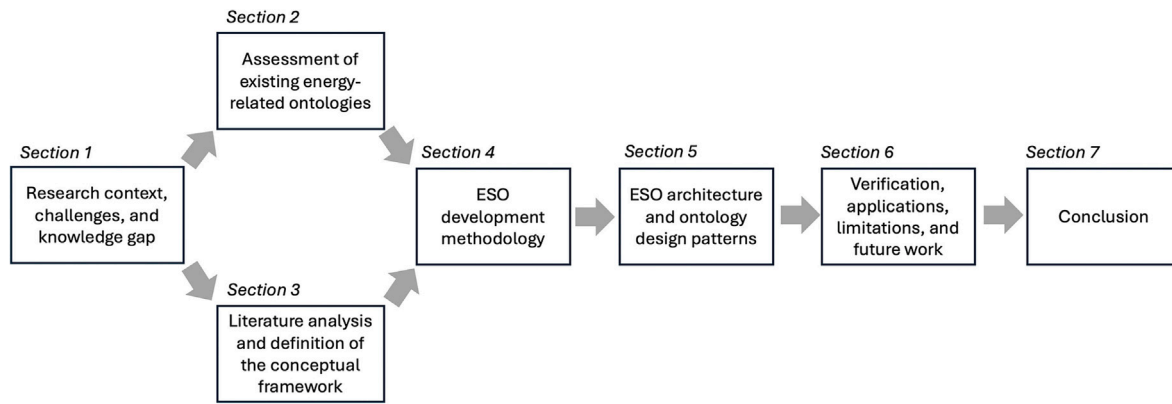


Fig. 1. Conceptual flow of the manuscript and logical relationships among its main sections.  
Source: Authors.

sustain and reproduce” [12]. Thus, in the light of the presented ontology, “the social” is presented not as a separate subsystem, but rather as a pattern of recurring relations among various elements, activated differently across different domains.

In this work, we introduce both a conceptual framework and an ontology engineering methodology to address the multidimensional nature of the energy transition. The conceptual framework organizes the domain into five interconnected layers representing the main subsystems of the energy socio-technical system, while the ontology engineering methodology follows a corpus-informed and expert-validated approach. Scientific-literature metadata provide the empirical basis for identifying candidate terminology, whereas term selection, semantic classification, harmonization, conceptualization, and formalization are conducted through an expert-guided ontology engineering process. The five-layer conceptual framework and the ontology engineering methodology therefore operate at two complementary levels: the former defines the analytical dimensions of the energy transition domain, while the latter identifies, evaluates, and formalizes domain concepts within this predefined structure.

ESO identifies the main concepts pertaining to energy transition and proposes 18 ontology design patterns. Most of the identified patterns address multiple energy subsystems. For example, the energy waste ontology design pattern, which focuses on the unnecessary or inefficient use of energy resources, encompasses subsystems related to the environment, policy, human behavior, and technology. Using ESO in relation to social practices allows us to go beyond questions concerning technology, supply, policies or resources and to examine the dynamics of energy-related actions undertaken by various actors operating in multidimensional assemblages of meanings, materialities and skills [13]. In this sense, the ESO is a flat ontology, where layers are distinguished not to order the reality hierarchically but rather to illustrate how different components interact and influence each other equally.

The need for the ontology to encompass multiple perspectives is also highlighted by Pfenninger et al. [14] and Booshehri et al. [15], who provided an overview of the gradual inclusion of various perspectives required to model the complexity of the energy domain. While perspectivism suggests that any understanding of a subject is inherently partial and shaped by the observer’s viewpoint [16], ESO aims to bring together these diverse perspectives into a comprehensive and coherent ontological representation of the energy system, with particular emphasis on the energy transition.

This work adopts a design science research perspective [17], aiming to construct and evaluate a formal ontology as a conceptual artefact intended to structure and integrate knowledge, rather than to provide predictive [18], decision-making [19], or prescriptive models of the energy transition. Accordingly, ESO is conceived as an epistemic infrastructure that supports the systematic organization, integration,

and comparison of knowledge across the multiple domains involved in the energy transition.

The contribution and structure of the manuscript are summarized in Fig. 1. Section 1 introduces the research context, the main challenges associated with the semantic representation of energy systems, and the resulting knowledge gap. Section 2 reviews related work on ontological approaches to energy system modeling and the energy transition. Section 3 introduces the five-layer conceptual framework developed through a literature review to structure the energy transition domain. Section 4 describes the corpus-informed and expert-validated ontology engineering methodology used to construct ESO. Section 5 presents the core concepts and ontology design patterns that constitute ESO. Section 6 discusses the verification of the ontology, its potential applications, its limitations, and directions for future work. Finally, Section 7 summarizes the main conclusions of the study.

## 2. Related work on energy ontologies

A wide range of ontologies has been developed to represent knowledge related to energy systems, covering different levels of granularity and application contexts. Some of these ontologies extend beyond the energy domain to capture its interactions with other sectors, such as environmental, health, economic, and market systems, while others focus on more specific contexts in which energy plays a central role, including households and smart cities.

These ontological resources have been designed to address a variety of objectives. In some cases, they aim to enable interoperability across heterogeneous data sources [20]; in others, they support decision-making processes and analytical applications [21]. Furthermore, several ontologies contribute to improving communication among stakeholders by providing a shared vocabulary of concepts and clearly defined relationships [15].

The analysis of existing ontologies serves two main purposes. First, it aims to identify potential gaps in current knowledge representations that need to be addressed by ESO. Second, it seeks to explore possible connections with existing ontologies that could be integrated into the ontology. The literature reviews by De Nicola & Villani [22] and Pritoni et al. [23] served as key references for identifying relevant links and information on existing ontologies. Although these reviews sometimes focus on specific aspects of the energy domain, they provide a valuable overview of the current state of research in this field. Below, we present the results of our analysis, including a list of selected ontologies along with brief descriptions.

The Open Energy Ontology (OEO) [15] is a domain ontology developed in the Web Ontology Language (OWL)<sup>1</sup> to enhance semantic

<sup>1</sup> Web Ontology Language (OWL) url: <https://www.w3.org/OWL/>.

interoperability, data annotation, and model coupling in energy systems analysis. Structured into three main modules, i.e., oeo-physical, oeo-model, and oeo-social, it provides detailed representations of technological infrastructures, energy carriers, emissions, models, scenarios, and socio-economic actors.<sup>2</sup>

The ETS-Related European Ontology (EREON) [21,24] is a policy-oriented ontology designed to formally represent the European Union Emissions Trading System (EU ETS). It models emissions allowances, compliance mechanisms, regulated sectors, and interactions between enterprises and regulatory authorities. Beyond allowance trading, EREON incorporates concepts related to low-carbon technologies, energy systems, environmental impacts, and climate policy instruments, supporting policy analysis and decision-making. EREON is primarily focused on regulatory and operational aspects of emissions governance.

The Sustainable Development and Climate (SDC) ontology<sup>3</sup> provides a semantic model of the interactions between climate change and the water-energy-food nexus within the broader framework of the Sustainable Development Goals (SDGs). It represents greenhouse gases, energy supply, fuels, natural resources, and human populations, capturing socio-ecological interdependencies and their environmental impacts. By extending upper-level entities and reusing elements from the Common Core Ontologies [25], SDC supports interoperability across sustainability domains.

PowerOnt<sup>4</sup> [26] is an ontology integrated with DogOnt [27], designed to model energy consumption and device-level interactions in smart homes and smart environments. Its primary focus lies in the operational management of appliances and their interoperability within domestic energy settings. Through DogOnt, it enables detailed semantic descriptions of smart devices, including their location, functional capabilities, technological interfaces, configuration states, and relationships with the surrounding environment, such as architectural elements and household equipment.

SAREF4ENER<sup>5</sup> [28] is an ontology developed as an extension of the Smart Appliance REFERENCE (SAREF) ontology<sup>6</sup> [29]. Designed to support semantic interoperability in the energy domain, it provides concepts for modeling power profiles, energy consumption and production, and demand-response mechanisms in smart appliances and smart grid environments. It enables detailed operational representation of device-level energy management.

The Energy Knowledge Graph (EKG), proposed by Chun et al. [30], is an ontological framework designed to model and integrate smart grid and microgrid systems. It defines an upper-level structure comprising entities such as smart grid entities, resources, services, processes, events, participants, communities, and devices. The EKG supports both technical and business scenarios, including energy trading, demand-supply balancing, storage management, and service orchestration, enabling strategic configuration and reconfiguration of microgrids. Its primary focus is the operational and service-level management of distributed energy systems.

DEHEMS (Digital Environment Home Energy Management System) [31] is an ontology developed within an EU-funded project aimed at monitoring and analyzing energy consumption in domestic environments. It provides a semantic framework for representing real-time and historical data on appliance-level electricity use, supporting feedback mechanisms and behavioral change interventions to improve household energy efficiency. Its core contribution lies in operational management of device-level energy data.

**Table 1**

Qualitative comparison of the representational scope of selected energy ontologies across the five analytical subsystems.

| Ontology   | Environment | Strategy | Policy | Behavior | Operations |
|------------|-------------|----------|--------|----------|------------|
| DEHEMS     | ○           | ◐        | ○      | ◐        | ●          |
| EKG        | ◐           | ●        | ◐      | ◐        | ●          |
| EREON      | ◐           | ◐        | ●      | ◐        | ●          |
| ESO        | ●           | ●        | ●      | ●        | ●          |
| OEO        | ◐           | ◐        | ◐      | ◐        | ●          |
| PowerOnt   | ◐           | ○        | ○      | ◐        | ●          |
| SAREF4ENER | ◐           | ◐        | ◐      | ◐        | ●          |
| SCO        | ◐           | ◐        | ◐      | ◐        | ◐          |
| SDC        | ●           | ◐        | ◐      | ◐        | ◐          |

○ no explicit coverage ◐ limited coverage ◑ moderate coverage ◒ substantial coverage ● strong coverage Source: Authors.

The Smart City Ontology (SCO)<sup>7</sup> [32] provides a knowledge representation of smart cities, structuring the physical, social, digital, and governance dimensions of urban systems. First introduced in 2015 (SCO 1.0) to assess electronic applications and smart city services, it has evolved into SCO 2.0, which adopts an architecture based on the Basic Formal Ontology (BFO) to model urban components, planning processes, governance structures, environmental context, and digital infrastructures. Energy systems are included as an urban subsystem within a broader smart city framework.

To support a consistent comparison, the selected ontologies were assessed using the five-layer conceptual framework presented in Section 3. These layers were derived from the multidisciplinary literature synthesis discussed in that section and are used here as analytical dimensions for examining the scope and coverage of existing ontologies. The comparison is qualitative and assesses the representational scope of each ontology with respect to the five analytical dimensions of the framework. To make the assessment criteria explicit and consistently applicable across the selected ontologies, the following rubric was adopted: *no explicit coverage* indicates that the subsystem is not explicitly represented; *limited coverage* indicates the presence of only isolated concepts related to the subsystem, without an articulated representation of its main components or relations; *moderate coverage* indicates that several relevant concepts and some relationships are represented, while important aspects of the subsystem remain absent or peripheral; *substantial coverage* indicates that the main conceptual categories and relationships of the subsystem are explicitly represented, although some relevant aspects remain outside the ontology's scope; and *strong coverage* indicates that the subsystem constitutes an explicit and articulated component of the ontology, including its principal conceptual categories, internal relations, and relevant connections with other represented dimensions.

Each ontology was assessed using these definitions as a common qualitative scoring rubric. The assessment was conducted by the authors on the basis of the publicly available ontology resources and associated documentation. The resulting scores therefore represent an internally conducted evaluation of representational scope rather than an independent assessment of ontology quality and may retain a degree of subjective interpretation.

Our comparative assessment highlights significant differences in how existing energy ontologies represent the various dimensions of energy systems. Table 1 summarizes this assessment by classifying the selected ontologies according to the five layers of the conceptual framework: environment, strategy, policy, behavior, and operations. Most ontologies provide strong coverage of operational aspects, particularly device-level modeling, smart grids, and data interoperability. By contrast, environmental constraints, policy mechanisms, strategic orientations, and behavioral dynamics are often addressed only partially or remain peripheral to their core modeling structures. Only a limited number

<sup>2</sup> Open Energy Family url: <https://openenergy-platform.org/about>.

<sup>3</sup> Sustainable Development and Climate (SDC) ontology url: <https://github.com/hbabaie1/Sustainable-Development-and-Climate-SDC-ontology>.

<sup>4</sup> PowerOnt url: <https://sites.google.com/site/smartappliancesproject/ontologies/dogpower-ontology>.

<sup>5</sup> SAREF4ENER ontology url: <https://saref.etsi.org/saref4ener/v1.1.2/>.

<sup>6</sup> SAREF ontology url: <https://saref.etsi.org>.

<sup>7</sup> Smart City Ontology (SCO) url: <https://urenio.org/smart-city-ontology/>.

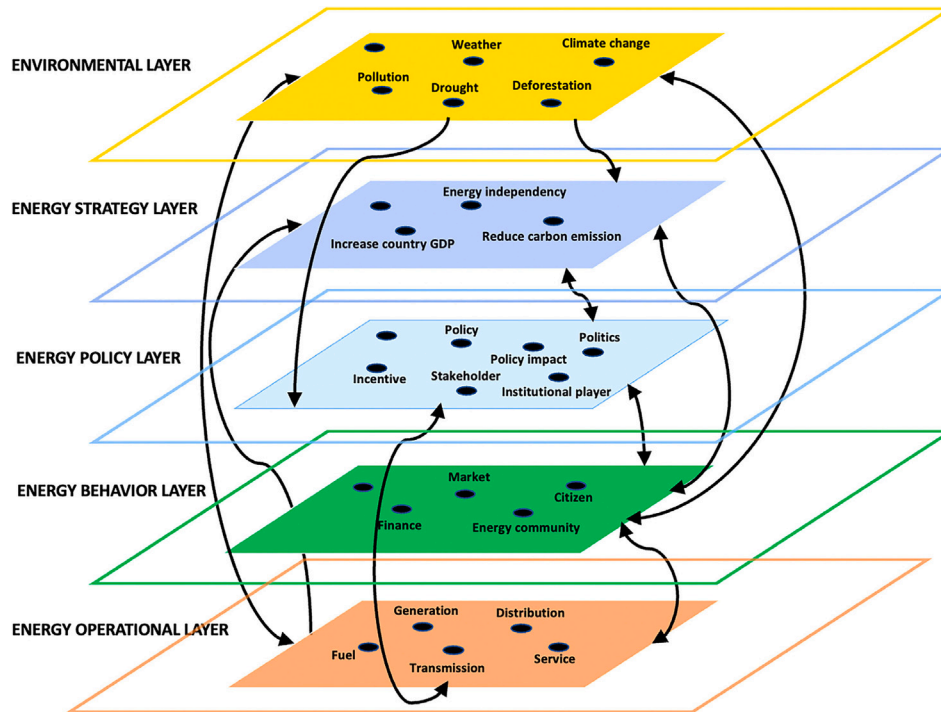


**Fig. 2.** Conceptual framework serving as the basis for structuring the Energy System Ontology. The arrows indicate directional influences across layers, including feedback loops between operational, behavioral, policy, strategic, and environmental dimensions.

Source: Authors.

of ontologies provide a comparatively balanced representation across technical, socio-economic, institutional, and environmental dimensions.

The comparison is therefore intended to characterize differences in representational scope with respect to the adopted five-layer framework and should not be interpreted as a general ranking of the scientific or technical quality of the considered ontologies. In particular, it shows how ESO applies the literature-derived framework by explicitly representing all five layers and the interdependencies among them. The comparative assessment should therefore be understood as an analysis conducted after the definition of the conceptual framework, rather than as the basis from which the framework was constructed.

### 3. The conceptual framework of the Energy System Ontology

Energy transition research encompasses a wide range of heterogeneous dimensions, including the environmental context, technological infrastructures, regulatory mechanisms, and social dynamics. These dimensions are often investigated in isolation, resulting in fragmented representations that hinder the systematic integration and comparison of knowledge across disciplines. From a knowledge modeling perspective, this fragmentation represents a significant challenge, as it limits the ability to capture the interdependencies that characterize energy systems as complex socio-technical phenomena.

To address this issue, we introduce a conceptual framework that provides an analytical structure for organizing the energy transition domain. Rather than representing the domain through isolated categories, the framework identifies a set of interrelated layers that capture the main sources of variability within energy systems and their transformation processes. The framework was developed through a review of the literature, with the aim of balancing the specificity of the identified layers with the need for a high-level, general representation. It should not be interpreted as a rigid decomposition, but rather as an analytical device for capturing cross-domain interactions.

The framework distinguishes five core layers, corresponding to environmental context, strategic orientations, policy instruments, behavioral dynamics, and operational processes (see Fig. 2). The environmental

context captures the natural and physical conditions, including climate dynamics and pollution, within which energy systems evolve. Strategic orientations reflect long-term directions and objectives, such as energy transition pathways and energy security goals, that shape system transformations. Policy instruments represent the set of regulatory and institutional mechanisms, including incentives and penalties, through which these strategies are implemented. Behavioral dynamics capture the actions and responses of individuals, organizations, and market actors. Operational processes describe the technological and organizational activities that underpin the energy value chain, from production to distribution and final service provision, thereby enabling the overall functioning of the energy system. Table 2 makes explicit the evidence base underlying the conceptual framework. It summarizes examples of the main themes identified in the reviewed literature and clarifies how they informed the definition of the five layers and their interconnections. The framework resulting from this synthesis was subsequently used as the analytical structure for assessing the coverage of existing energy-related ontologies in Table 1.

The five layers are strongly interconnected (see Fig. 2), and in many cases, such as the interaction between the environmental and operational layers, the relationships are reciprocal, as indicated by the bidirectional arrows. In particular, energy operations and environmental conditions are linked through tightly coupled feedback mechanisms. On the one hand, energy-related activities have a direct impact on the environment [33–36]; on the other hand, environmental changes, in turn, influence the functioning and performance of energy systems [37–43]. For example, electricity generation contributes to anthropogenic emissions, including CO<sub>2</sub> [44], while climate-related phenomena such as extreme heat events can in turn affect system operations by increasing electricity demand for cooling, thereby placing additional stress on energy operations [45]. This layered representation enables a more systemic understanding of the energy transition, supporting the integration of heterogeneous knowledge across environmental, technological, policy, and societal dimensions.

**Table 2**  
Literature basis of the conceptual framework presented in Fig. 2.

| Layer                         | Themes (examples)                                                                                                                                                  | Contribution to the conceptual framework                                                                                                                                                                                                                                                                                                                          | References                         |
|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|
| Environment                   | Climate change, pollution, emissions, natural-resource constraints, environmental impacts, and climate-related effects on energy systems.                          | This layer defines the natural and physical context within which energy systems operate. The literature also supports a reciprocal relationship between this layer and energy operations: energy activities affect environmental conditions, while climate and environmental changes influence energy demand, generation, infrastructure, and system performance. | [33–45]                            |
| Strategy                      | Long-term energy-system objectives, transition pathways, energy security, energy independence, sustainability, and net-zero ambitions.                             | This layer represents the long-term orientations that guide energy-system transformation. Strategic priorities are shaped by environmental pressures, technological developments, market conditions, and policy frameworks, and in turn influence operational and policy choices.                                                                                 | [46–54]                            |
| Policy                        | Regulation, incentives, penalties, institutional arrangements, governance mechanisms, renewable-energy support, and technology-adoption measures.                  | This layer captures the institutional instruments through which strategic objectives are translated into interventions. The literature shows that policies shape technological deployment and social behavior, while operational innovation, stakeholder action, and environmental pressures can also stimulate policy change.                                    | [55–65]                            |
| Behavior                      | Energy-use practices, responses to prices and disruptions, technology adoption, energy communities, and sustainable behavior.                                      | This layer represents how individuals, communities, organizations, and market actors respond to policy, prices, environmental conditions, and system performance, while shaping demand, markets, environmental outcomes, and policy.                                                                                                                              | [46,47,66–76]                      |
| Operations                    | Energy technologies, infrastructure, and processes across the energy supply chain, from production to end use.                                                     | This layer represents the technological and organizational processes that enable the functioning of the energy system. Operational developments influence strategies, policies, environmental outcomes, and user behavior, while these layers constrain or redirect operational activities.                                                                       | [45,55–57,59]                      |
| Interconnections among layers | Feedback mechanisms, socio-technical interactions, policy–technology co-evolution, behavioral responses, environmental constraints, and cross-domain dependencies. | The five layers form an interconnected system rather than independent categories. The reviewed literature provided evidence of reciprocal and directional influences among environmental, strategic, policy, behavioral, and operational processes.                                                                                                               | [11,12,46,47,50,55,57,59,60,71,77] |

Source: Authors.

The interactions among the five subsystems should not be interpreted as unidirectional flows. In ESO, feedback mechanisms can be represented as closed directed paths that connect concepts and relations across the integrated ontology. These paths may remain local to a subsystem or cross environmental, policy, behavioral, operational and other subsystem boundaries. ESO represents the semantic constituents and direction of these feedbacks, but not their quantitative dynamics, polarity, magnitude, or temporal delay.

The energy strategy layer is closely linked to the operational layer, as technological developments can shape strategic decision-making. In particular, advancements in energy operations may influence the formulation and revision of energy strategies. For example, the large-scale deployment of breakthrough energy technologies could prompt countries to reassess their strategic priorities, potentially leading to reduced dependence on specific energy sources.

A bidirectional relationship also exists between the operational and policy layers. Developments at the operational level can influence policy decisions; for example, the emergence of more sustainable technologies and appliances may encourage governments to introduce incentives to support their adoption [55,56]. Conversely, policy interventions can actively shape operational dynamics by promoting specific technological pathways. Measures aimed at accelerating the uptake of innovations, such as electric vehicles, can foster further technological development and diffusion within the sector [55,57–59,64]. In addition to technological drivers, institutional and governance-related factors also play a role. Recent studies indicate that characteristics of decision-making bodies, including gender diversity, can affect the resilience of renewable energy supply chains, thereby influencing operational vulnerabilities through policy design and governance choices [65].

The operational layer also interacts with the behavioral dimension of the energy system. Disruptions in energy services, such as blackouts or outages, can directly influence consumption patterns by altering how citizens use and manage energy [46,47,66,67]. Conversely, behavioral factors, such as inefficient or excessive energy use, can increase demand, thereby requiring higher levels of energy production within power systems.

The behavioral dimension of the system can also affect environmental context. For instance, patterns such as energy waste or distortions introduced by subsidized fossil fuel markets may lead to

increased pollution levels and contribute to climate change [68–70,77]. Conversely, environmental and climate-related changes can influence energy-related behaviors [71–75], shaping how individuals and communities consume energy. These responses may promote more sustainable practices, such as the adoption of energy-efficient technologies and cleaner modes of transport, but can also result in higher consumption, for example through the increased use of air conditioning during periods of extreme heat.

A bidirectional relationship can also be observed between the energy strategy and energy behavior layers. Market dynamics, such as increases in energy prices, may influence strategic objectives at the national level, including targets related to the Gross Domestic Product (GDP) [46,47,78]. Conversely, strategic choices, such as pursuing energy independence through the reduction or suspension of energy trade between countries, can shape financial and market behaviors within the energy sector [46–49].

A reciprocal relationship also links the behavioral and policy dimensions of the energy system. Policy measures introduced by institutional actors, such as incentives, tax relief schemes, and regulatory frameworks promoting renewable energy production and consumption, can stimulate collective initiatives like energy communities [60–63,76]. In turn, these communities increasingly act as active stakeholders, influencing the policy landscape by advocating for regulatory improvements, addressing legal gaps, and supporting the evolution of energy transition policies [50,55,57,79–81].

A bidirectional relationship also characterizes the interaction between the energy strategy and policy layers. Strategic orientations can guide the design of policy measures; for instance, a focus on energy independence may lead countries to promote domestic energy production based on locally available resources, such as solar or wind [46,50]. Conversely, policy frameworks shape strategic trajectories by defining targets, timelines, and regulatory conditions for achieving objectives such as net-zero emissions [46].

The energy strategy layer is strongly influenced by environmental context. In particular, growing environmental concerns, such as the observed rise in global temperatures, have contributed to a shift in strategic priorities, moving from a focus primarily on energy access and security towards approaches that also incorporate the sustainability of energy systems, as reflected in energy transition strategies [51–54].

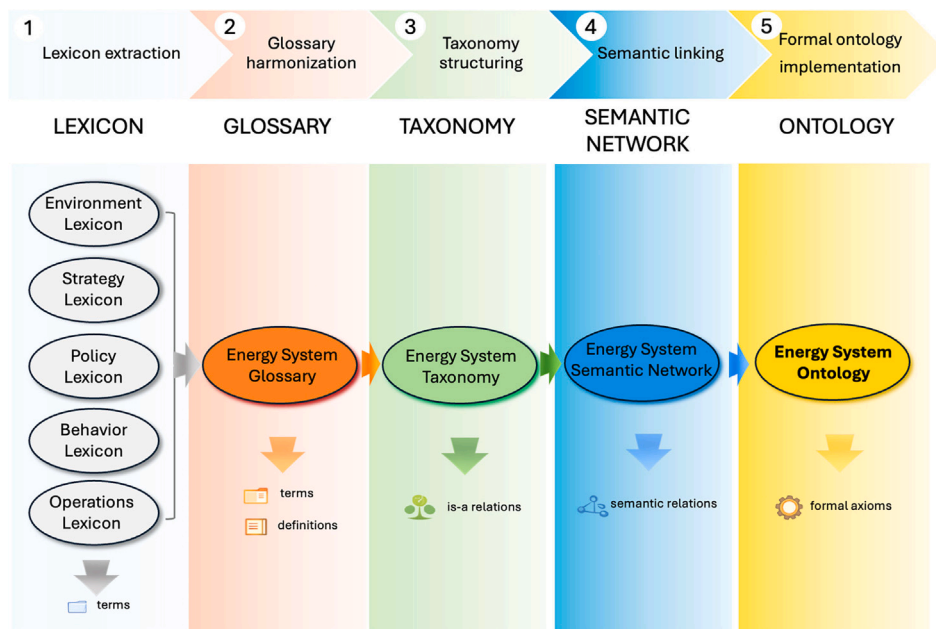


Fig. 3. Ontology engineering methodology used for building ESO.  
Source: Authors.

Environmental context also plays a key role in shaping energy policy [41,82,83]. For instance, elevated levels of pollution associated with fossil fuel emissions can prompt the introduction of regulatory measures, such as penalties for high-emission activities and incentives for cleaner technologies, to support the transition towards low-carbon energy systems.

The conceptual framework of ESO ultimately provides the structural foundation for our multidisciplinary approach, enabling the coherent integration of the diverse subsystems involved in energy transition processes. Each layer informs the modularization of the ontology through dedicated ontology design patterns, providing a direct link between the conceptual framework and its formal representation.

## 4. Ontology engineering approach and development process

### 4.1. Methodological framework for ontology development

To develop ESO, we adopted an ontology engineering methodology, understood as a structured framework that guides the design, development, and maintenance of ontologies. Such methodologies play a key role in ensuring both the reproducibility of the modeling process and the quality and consistency of the resulting ontology.

A number of ontology engineering methodologies have been proposed in the literature, including METHONTOLOGY [84], OntoKnowledge [85], UPON [86], NeOn [87], GOSPL [88], and UPON Lite [6]. While these approaches provide comprehensive frameworks for ontology development, many of them are relatively complex and resource-intensive, and are often tailored to experienced ontology engineers rather than to interdisciplinary teams involving domain experts.

For this reason, we adopted UPON Lite as a starting point, given its lightweight and flexible nature, and adapted it to the specific requirements of the energy system domain. In particular, the methodology was tailored to account for the interdisciplinary composition of the development team and the use of automated tools supporting the ontology construction process. Consistent with UPON Lite, the adopted approach relies on the combined expertise of ontology engineers and domain experts. The methodology is articulated into five main activities, illustrated in Fig. 3, which were implemented as follows: (i) lexicon extraction,

(ii) glossary harmonization, (iii) taxonomy structuring, (iv) semantic linking, and (v) formal ontology implementation.

### 4.2. Development of the energy system ontology

The implementation of the five ontology engineering activities introduced above is described in detail in the following.

#### 4.2.1. Lexicon extraction

The construction of the lexicon followed a corpus-informed and expert-validated procedure aimed at identifying terminology used across the multidisciplinary energy transition literature. The objective of this activity was not to generate the ontology automatically from bibliographic data, but to derive an empirical set of candidate terms to be subsequently evaluated, harmonized, and formalized by domain experts and ontology engineers.

The bibliographic corpus was retrieved from Scopus on 17 March 2023 using the query TITLE-ABS-KEY("energy transition" OR "energy transformation"). The search returned 17,591 records, of which 15,367 contained indexed keywords and were therefore retained for terminology extraction. These records contained 58,226 keyword occurrences. As an initial noise-reduction step, only keywords occurring more than six times in the corpus were retained, reducing the candidate terminology to 4582 keywords. The threshold should therefore be understood as a pragmatic filtering choice intended to balance three competing requirements: reducing the large number of low-frequency terms likely to provide limited support for recurrent domain terminology, retaining a sufficiently broad and heterogeneous candidate lexicon, and keeping the number of terms manageable for systematic expert assessment. The sensitivity analysis shows that neighboring cut-off values progressively change the size of the candidate set without revealing a sharp discontinuity around the selected threshold. The cut-off was therefore not treated as a theoretically optimal boundary, but as a reproducible preprocessing decision preceding expert-based conceptual inclusion.

The classification of terms was carried out through an expert-driven multilabel assessment. Six domain experts in energy transition research independently evaluated the pertinence of each candidate keyword to each of the five subsystems. Since energy transition concepts may

span disciplinary boundaries, the same keyword could be associated with more than one subsystem. Inter-rater reliability was assessed on these initial judgments, before any consensus-building activity, using Fleiss' kappa [89]. Since the classification task was multilabel, each keyword–subsystem association was treated as a binary decision (pertinent/not pertinent). The mean raw agreement among the six experts was 0.852 for Environment, 0.864 for Strategy, 0.738 for Policy, 0.755 for Behavior, and 0.694 for Operations, with an overall mean agreement of 0.781. Fleiss' kappa, which accounts for agreement expected by chance, was calculated separately for each subsystem and across the complete set of assessments. The resulting values were 0.249 for Environment, 0.122 for Strategy,  $-0.009$  for Policy, 0.096 for Behavior, and 0.239 for Operations, with an overall value of 0.175. These results show that, although the observed raw agreement was relatively high, chance-corrected inter-rater reliability was limited and varied across subsystems.

The relatively low Fleiss' kappa values should be interpreted in light of the multidisciplinary and multilabel nature of the classification task. The expert panel included heterogeneous disciplinary backgrounds spanning social sciences, economics, policy-making, technological, and environmental aspects of energy systems, while many energy-transition concepts may legitimately pertain to more than one subsystem. The observed variation across subsystems may therefore reflect both differences in disciplinary interpretation and the inherently overlapping semantic boundaries of the five analytical subsystems. For this reason, the initial independent assessment was followed by a structured consensus-building and majority-voting procedure, described below, to determine the final keyword assignments.

During the structured consensus-building procedure, cases showing divergent assessments were discussed collectively to clarify possible differences in interpretation. The final inclusion of each keyword in a subsystem was then determined by majority vote among the six experts. A keyword was retained for a subsystem when at least four of the six experts assessed it as pertinent. Since the classification was multilabel, the same keyword could be retained in more than one subsystem. This process resulted in five subsystem-specific lexicons.

The resulting lexicons were then further refined to address terminological redundancy. Synonymous and semantically equivalent expressions were manually identified and grouped into synsets, following the notion introduced in WordNet,<sup>8</sup> where a synset represents a set of terms that can denote the same concept within a given context. This harmonization resulted in 1980 synsets across the five subsystem lexicons. The resulting synsets constituted the lexical input to the subsequent glossary-harmonization and ontology-formalization activities.

#### 4.2.2. Glossary harmonization

The glossary harmonization activity of the methodology focused on establishing clear and consistent definitions for the concepts included in the lexicon. Building on the previously defined subsystems, the terms, organized into synsets, were assigned to domain experts, who were responsible for formulating definitions grounded in the relevant scientific literature.

To ensure consistency and interoperability, existing vocabularies and ontological resources were consulted whenever appropriate. In particular, reference sources such as WordNet and the Open Energy Ontology were used to align definitions with established terminologies when suitable matches were available.

The definition process was further supported by the use of tools based on artificial intelligence (AI) to assist in drafting preliminary descriptions. These outputs were not adopted directly; instead, they were

systematically reviewed, refined, and validated by domain experts to ensure conceptual accuracy and avoid potential inconsistencies associated with automated text generation [90].

#### 4.2.3. Taxonomy structuring

The taxonomy structuring activity addressed the organization of the identified concepts into a hierarchical structure based on generalization–specialization (IsA) relationships. The resulting taxonomy provides a structured view of the domain, where concepts are arranged according to different levels of abstraction, enabling a coherent representation of both general and domain-specific notions.

To ensure semantic consistency and interoperability, the taxonomy was grounded in the Basic Formal Ontology (BFO) [91], a widely adopted foundational ontology. Similar to other upper-level ontologies such as the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) [92], the Suggested Upper Merged Ontology (SUMO) [93], and the Unified Foundational Ontology (UFO) [94], BFO offers a set of high-level categories and relations that support modeling across heterogeneous domains. Its adoption facilitates alignment with existing ontological resources and promotes integration across information systems.

Within BFO, the most general category is that of entity, which is further distinguished into continuants and occurrents. Continuants are entities that persist through time while maintaining their identity, including independent continuants (e.g., physical objects such as batteries) and dependent continuants, such as qualities (e.g., energy or power), functions (e.g., strategies or policies), and roles (e.g., consumer or producer). Occurrents, in contrast, correspond to entities that unfold over time, such as processes, events, or activities, including their temporal boundaries and the spatiotemporal regions in which they occur. All concepts included in the glossary were mapped onto these foundational categories.

Building upon this foundational layer, the taxonomy was further refined through additional levels of specialization to better capture the structure of the energy transition domain. Particular attention was devoted to the concept of role, given its relevance to representing the different ways in which actors participate in energy transition processes. This concept was therefore articulated into multiple, non-mutually exclusive subclasses reflecting different analytical perspectives, allowing a single entity to simultaneously assume different roles. Within ESO, the role hierarchy includes actor-related specializations representing professional, institutional, societal, and market-related forms of participation. These include, among others, operators, policymakers, researchers, civil-society actors, communities, energy consumers, stakeholders, and market participants. More specialized concepts further distinguish specific forms of participation; for example, energy market participants include energy distributors, end users, producers, providers, retailers, and suppliers. This structure allows actors to be represented according to the roles they assume in different energy-system contexts.

#### 4.2.4. Semantic linking

The semantic linking activity focused on enriching the semantic expressivity of the ontology by defining domain-specific relationships between concepts. To this end, we identified 18 ontology design patterns tailored to the energy transition domain, which constitute the backbone of ESO and support its future extension. The identification of these ODPs was informed by a systematic analysis of the literature and domain expertise spanning engineering, environmental sciences, economics, and social studies. This combined approach enabled the abstraction of recurring conceptual structures and their formalization into reusable modeling patterns. While several ODPs were developed specifically for this work to address gaps in existing representations, others, such as the risk and system aspect patterns, build upon and adapt established conceptualizations from the literature [95] to ensure theoretical grounding and semantic alignment with prior research.

<sup>8</sup> WordNet url: <https://wordnet.princeton.edu>.

An ODP is a reusable and generalizable conceptual model fragment or template used to represent and model knowledge in an ontology. ODPs aim at modeling complex relationships, attributes, and entities within an ontology to make the ontology modular, interoperable, and easier to understand [7]. Each ODP addresses one or more subsystems, reflecting the extent to which a given conceptual pattern captures interactions spanning environmental, strategic, policy, behavioral, and operational dimensions. The 18 ODPs are listed in Fig. 4, which visually summarizes their distribution across the five conceptual subsystems of ESO. The figure highlights both narrowly focused patterns, which are primarily associated with a single subsystem, and more integrative patterns that explicitly bridge multiple subsystems. This representation provides an immediate overview of the multidimensional scope of each ODP and anticipates the degree of interdisciplinarity embedded in the ontology's core structures.

The proposed set of ODPs should be interpreted as a flexible and evolving component of the ontology, rather than as a fixed or exhaustive specification. In this sense, the ontology is conceived as a living entity, progressively refined and extended as new knowledge, perspectives, and modeling needs emerge within the energy transition domain. Accordingly, the absence of explicitly defined relationships or patterns does not imply that such relationships do not exist, but rather that they have not yet been formalized within the current scope. Consequently, missing axioms cannot be interpreted as false statements, nor can they be used by a reasoner to infer their invalidity, in accordance with the *open-world assumption* [96]. This perspective supports the continuous integration of interdisciplinary knowledge across technological, policy, and societal dimensions of the energy transition.

The concepts within the ODPs form the core of the ESO, allowing them to be extended through specialization relationships to capture the nuances of the energy transition domain. In the next section, we describe in detail some of the identified patterns.

Within this architecture, BFO and ESO's ontology design patterns operate at different levels. BFO provides the foundational ontological categories used to distinguish, for example, objects, qualities, roles, and processes. ESO's domain upper ontology is instead constituted by reusable energy-domain structures that specialize these foundational categories and can be further extended to represent more specific knowledge. Consequently, ESO is not intended to pre-encode every entity, attribute, or parameter that may occur in an energy dataset, model, or information standard. Its purpose is to provide reusable semantic structures through which more specialized domain knowledge can be represented consistently and related to a common conceptual framework.

A cross-cutting modeling structure concerns quantitative qualities. Several energy-domain concepts, such as capacity, rated power, efficiency, and stored energy, denote qualities whose magnitude must be associated with a numerical value and a measurement unit. To represent these cases uniformly, ESO introduces a quantitative-quality pattern. Quantitative quality is modeled as a specialization of the BFO class quality and is related to the entity in which it inheres through the inverse properties *hasQuality* and *isQualityOf*. A quantitative quality is associated through *hasQuantityValue* with a quantity value, modeled as a generically dependent continuant. The latter carries a decimal numeric value and a string-valued measurement unit. This structure separates the domain quality itself from the information used to specify its magnitude and can therefore be specialized for different quantitative characteristics without introducing ad hoc datatype properties for individual domain entities.

#### 4.2.5. Ontology formalization and implementation

The Energy System Ontology was implemented using the Protégé ontology management system [97] and is made available in the Resource

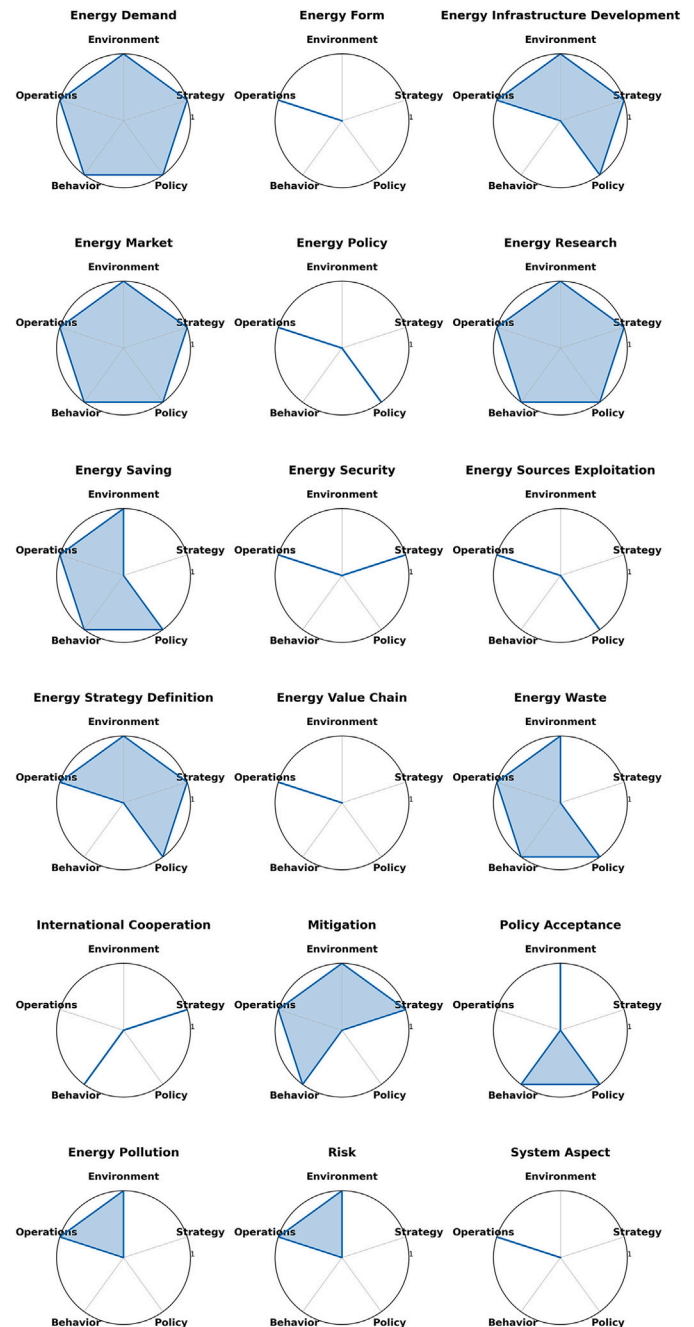


Fig. 4. Radar charts showing the distribution of each ODP across the five conceptual layers of the energy system: environmental, strategic, policy, behavioral, and operational. Each chart highlights the multidimensional scope of an individual ODP.

Source: Authors.

Description Framework (RDF)<sup>9</sup> and OWL formats. The ontology is conceived as a knowledge graph that can be progressively extended and integrated with external semantic resources.

To ensure both semantic rigor and interoperability, ESO was aligned with a set of well-established ontologies and vocabularies (see Fig. 5). In

<sup>9</sup> Resource Description Framework (RDF) website. <https://www.w3.org/RDF/>.

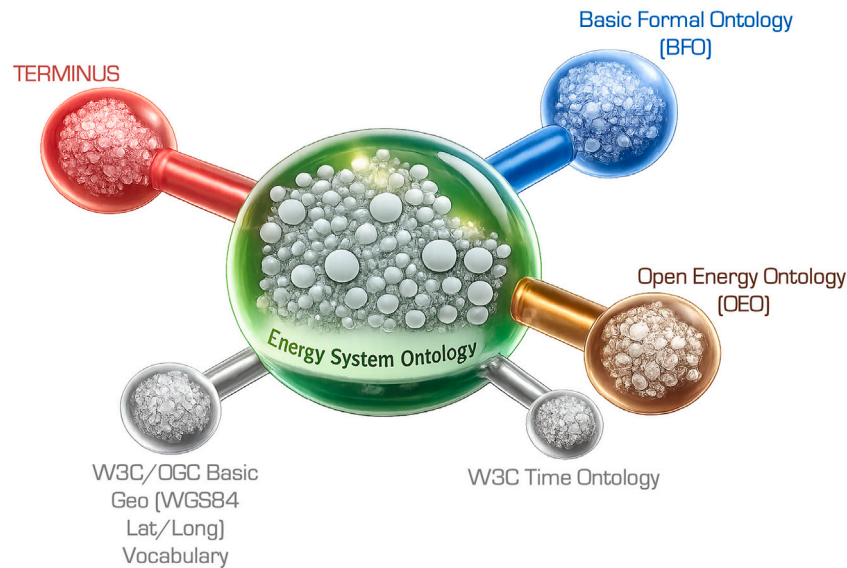


Fig. 5. Interconnections among the Energy System Ontology, TERMINUS, BFO, W3C/OGC Basic Geo Vocabulary, W3C Time Ontology, and the Open Energy Ontology. Source: Authors.

particular, the Basic Formal Ontology provides the foundational structure, supporting a consistent representation of entities and their relationships across different levels of abstraction. The Open Energy Ontology was integrated to facilitate interoperability with existing energy-related semantic resources, while TERMINUS (TERritorial Management and INfrastructures ontology for institutional and industrial USage) [95,98] contributes domain-specific modeling patterns, particularly for representing system aspects and risk-related dimensions. In addition, the World Wide Web Consortium/Open Geospatial Consortium (W3C/OGC) Basic Geo Vocabulary and the W3C Time Ontology were reused as foundational semantic resources for representing geographical and temporal entities. Their role in ESO is not to provide exhaustive domain-specific models of space and time, but to supply interoperable semantic anchors that can be specialized and connected to energy-domain concepts according to the granularity required by a given application. Thus, W3C Time provides generic representations of temporal entities, intervals, and durations, whereas the Basic Geo Vocabulary provides basic geographical entities and coordinates. ESO complements these generic structures with domain-specific concepts and relations specifying the role played by temporal and spatial entities within energy processes, infrastructures, markets, and investment decisions.

This extensibility is illustrated in the ontology through energy-specific temporal and spatial specializations. Regarding temporal granularity, for instance, the concepts electric load dispatching, energy storage, and investment are specialized through hourly electric load dispatching, seasonal energy storage, and multi-decade investment, respectively. These concepts are related to temporal entities from the W3C Time Ontology through domain-specific relations that distinguish their semantic roles: *hasTemporalResolution* specifies the time step at which a process is represented or performed, *hasCharacteristicStorageDuration* specifies the characteristic storage horizon, and *hasInvestmentHorizon* specifies the temporal horizon over which an investment is planned or evaluated. Hourly dispatch is therefore represented as a form of electric load dispatching having a one-hour temporal resolution, rather than as a process whose overall duration is necessarily one hour.

Regarding spatial granularity, geographical location is distinguished from electricity-network topology. ESO already includes concepts such as electricity network, network structure, transmission capacity, electric load flow, pricing, network node, network connection, and market zone, together with relations expressing network membership, connectivity,

and zone composition. A network node may be associated with a geographical point when coordinates are relevant, whereas a market zone represents a functional market aggregation of network nodes rather than merely a geographical or administrative region. Accordingly, nodal pricing and zonal pricing are represented as specializations of the existing pricing concept associated with a network node and a market zone, respectively. The Basic Geo Vocabulary therefore provides geographical reference, while ESO represents the functional topology and market role of the corresponding entities.

The ontological representation also makes explicit distinctions that are particularly relevant to renewable integration. ESO includes energy flexibility, power system flexibility, generation capacity, storage capacity, energy availability, energy reliability, transmission capacity, electric load flow, firm capacity, firm capacity assessment, transmission constraint, and transmission bottleneck. Flexibility denotes the capability of an energy resource or system to modify its operating state in response to changing conditions, whereas firm capacity denotes capacity that can be considered dependably available during a specified period and under specified assessment conditions. Transmission bottlenecks are represented as network conditions in which electricity transfer is constrained by the available transmission capacity of a network connection. These explicit semantic structures can additionally support application-specific inference rules, for example for classifying a network condition as a bottleneck on the basis of load-flow and available capacity values.

ESO also represents stranded assets as a specialization of asset within the system aspect structure and stranded asset risk as a specialization of risk. A stranded asset denotes an asset that experiences a premature reduction in economic value, expected return, or utilization as a consequence of changes in market, policy, technological, environmental, or other relevant conditions. This representation connects the economic implications of asset stranding to the reusable system aspect and risk structures already available in ESO.

From a structural perspective, ESO is organized around a core hierarchy based on *IsA* relationships, which is progressively specialized to capture domain-specific concepts. This core is complemented by a set of interconnected ontology design patterns, either developed within this work or adapted from existing ontologies. For example, patterns derived from TERMINUS, such as the system aspect pattern, are used to model operational characteristics of energy systems, in combination with foundational BFO concepts such as process, quality, and object.

**Table 3**  
Overview of the ontology design patterns included in ESO.

| ODP                               | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Energy demand                     | It represents energy demand as the outcome of interacting demographic, technological, environmental, behavioral, policy-related, and economic mechanisms, explicitly including energy market prices, price and income elasticity, income and substitution effects, and demand-response processes, together with the actors interested in or participating in demand dynamics.                                                                                                                                               |
| Energy form                       | It captures the different forms of energy and the processes through which energy is converted from one form into another.                                                                                                                                                                                                                                                                                                                                                                                                   |
| Energy infrastructure development | It models the development of infrastructures that enable energy production, transport, storage, and distribution, together with their objectives and stakeholders.                                                                                                                                                                                                                                                                                                                                                          |
| Energy market                     | It represents the energy market as an institutional and economic arrangement in which energy market participants trade energy commodities under specific market structures and market mechanisms. The pattern makes explicit how market structure, market power, supply, demand, system costs, policy instruments, and pricing mechanisms affect energy market prices, while also representing externalities, social costs, market failures, and policy-correction mechanisms such as carbon pricing, subsidies, and taxes. |
| Energy policy                     | It models energy policies as regulatory instruments connected to objectives, contextual factors, policy measures, stakeholders, and possible consequences.                                                                                                                                                                                                                                                                                                                                                                  |
| Energy research                   | It describes research activities related to the energy domain, including natural science, behavioral science, and design science contributions to energy knowledge.                                                                                                                                                                                                                                                                                                                                                         |
| Energy saving                     | It represents energy-saving behaviors and their effects on energy consumption, benefits, and user satisfaction.                                                                                                                                                                                                                                                                                                                                                                                                             |
| Energy security                   | It captures energy security as a strategic objective related to accessibility, availability, reliability, efficiency, sustainability, and the broader energy mix.                                                                                                                                                                                                                                                                                                                                                           |
| Energy sources exploitation       | It models the use of primary energy sources for specific energy uses, including the role of policy choices and the environmental consequences of exploitation.                                                                                                                                                                                                                                                                                                                                                              |
| Energy strategy definition        | It describes how energy strategies are formulated, relating strategic objectives to policy instruments, stakeholders, and implementation activities.                                                                                                                                                                                                                                                                                                                                                                        |
| Energy value chain                | It describes the main stages of the energy value chain, from primary sources and generation to transmission, storage, distribution, and end use.                                                                                                                                                                                                                                                                                                                                                                            |
| Energy waste                      | It models the inefficient or unnecessary use of energy resources, linking wasteful behavior to higher consumption, increased costs, and environmental impacts.                                                                                                                                                                                                                                                                                                                                                              |
| International cooperation         | It represents cooperative interactions among countries and international organizations aimed at addressing shared challenges and pursuing common energy-related goals.                                                                                                                                                                                                                                                                                                                                                      |
| Mitigation                        | It captures actions and strategies aimed at reducing negative consequences associated with hazards, critical events, and vulnerabilities affecting systems.                                                                                                                                                                                                                                                                                                                                                                 |
| Policy acceptance                 | It models the degree to which actors support or comply with policies, linking acceptance to internal and external behavioral drivers and policy support measures.                                                                                                                                                                                                                                                                                                                                                           |
| Energy pollution                  | It represents pollution as an environmental pressure generated by energy systems, linking pollutant sources to ecosystem vulnerability and ecological impacts.                                                                                                                                                                                                                                                                                                                                                              |
| Risk                              | It represents critical events affecting system aspects from the perspective of stakeholders, with particular attention to hazards and vulnerabilities.                                                                                                                                                                                                                                                                                                                                                                      |
| System aspect                     | It provides a general pattern for representing the perspectives from which a system can be described, such as services, operations, operators, assets, infrastructures, commons, spatial regions, and managed objects.                                                                                                                                                                                                                                                                                                      |

Source: Authors.

The current version of ESO<sup>10</sup> includes 2281 classes, 162 object properties, 33 data properties, and 13,249 axioms. Logical consistency was assessed using the Hermit reasoner in Protégé. Hermit successfully classified the ontology and completed inference precomputation without reporting inconsistencies; no named classes were inferred to be unsatisfiable.

This integration enables ESO to act as a semantic bridge across heterogeneous data sources and disciplinary perspectives.

## 5. Core concepts and analytical relationships of the energy system ontology

The Energy System Ontology provides a formal semantic structure for the systematic organization of concepts and relationships across the main subsystems of the energy transition, thereby facilitating reproducibility and comparability in review-based and model-oriented analyses.

The core concepts and relationships of ESO are derived from its ontology design patterns. Since many concepts are shared across multiple ODPs, they form an interconnected and extensible core network. Table 3 provides a concise overview of the ontology design patterns included in ESO, summarizing their conceptual scope and role within the energy transition domain. Next, we describe eight patterns together with their constituent concepts and relationships. To ensure transparency and reproducibility, the full initial set of ODPs is made available as a separate research deliverable developed within the GeneSys EU

project [99]. This article focuses on a selected subset for illustrative purposes; within this subset, the energy demand and energy market ODPs are further refined by making their demand-side economic mechanisms, market structures, price formation processes, externalities, and policy-correction mechanisms more explicit.

Each ODP is accompanied by a pictorial representation that illustrates its core ontological structure using a descriptive, intuitive notation without implying implementation-specific constraints.

Feedback mechanisms in ESO should be understood at the level of the integrated ontology rather than as necessarily closed structures within individual ODP diagrams. A feedback loop is represented as a closed directed semantic path, i.e., a sequence of explicitly represented relations that returns to a previously involved concept or subsystem. Because ODPs are modular views of selected portions of the ontology, the complete path may span multiple patterns and may therefore not appear graphically closed within a single figure. ESO captures the semantic structure and direction of such feedbacks, but does not encode quantitative dynamics such as magnitude, polarity, gain, or temporal delay, which require external causal, system-dynamics, or simulation models.

A representative example of logical closure across ESO subsystems can be illustrated by the relationship between climate change and urban mobility. Climate change may motivate the definition of an urban mobility decarbonization strategy, which can be implemented through a policy mix supporting the adoption of electric buses and the development of dedicated bus lanes. The adoption and deployment of electric buses concern the operational subsystem, as they involve changes in transport technologies and infrastructure. Together with the associated policy measures, these operational changes can affect

<sup>10</sup> Energy System Ontology url: <https://tinyurl.com/ESO-20260925>.

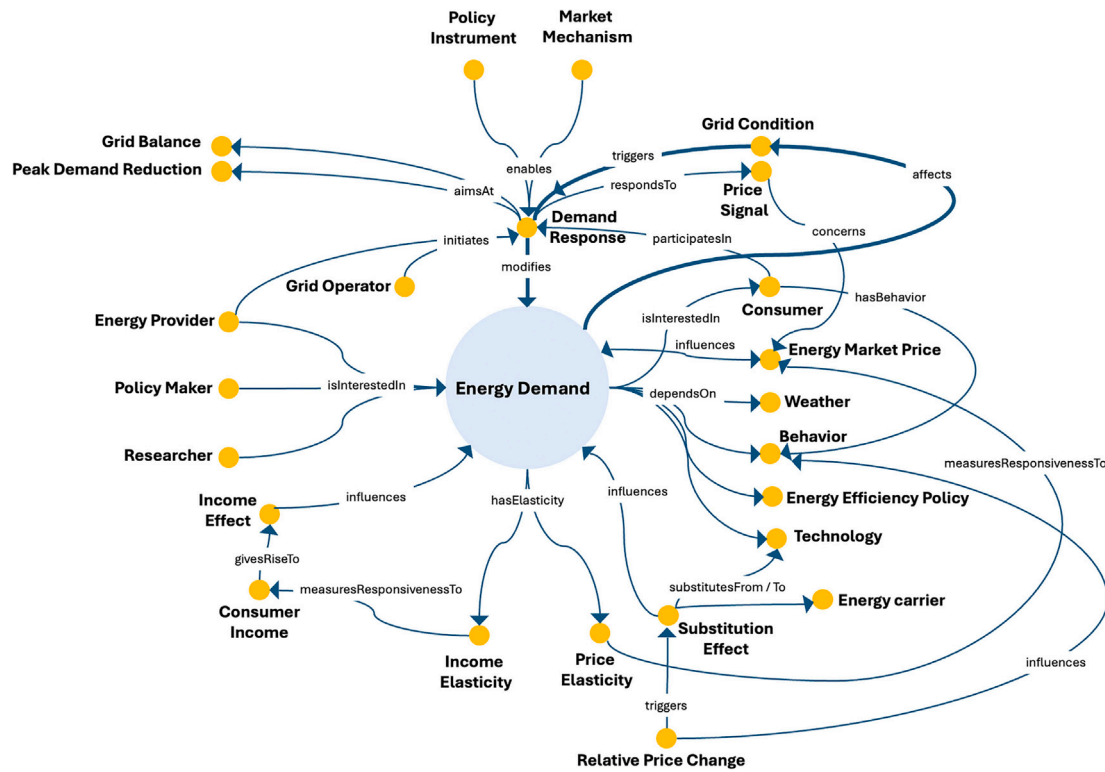


**Fig. 6.** Conceptual representation of the energy demand ontology design pattern, illustrating key actors, demand drivers, economic mechanisms, demand-response processes, and their relationships. Bold relations highlight the closed feedback path linking energy demand, grid condition, and demand response: energy demand affects grid condition, which can trigger demand response that, in turn, modifies energy demand.

Source: Authors.

social practices by encouraging a shift from private-car use to public transport for everyday mobility. Such behavioral changes may reduce fossil-fuel consumption and transport-related CO<sub>2</sub> emissions, thereby aligning the resulting system changes with climate-change mitigation objectives. Importantly, this feedback is not contained within a single ODP. Its logical closure emerges from the integration of concepts and relations distributed across several ODPs and ontology structures, including energy strategy definition, energy policy, energy infrastructure development, policy acceptance, energy pollution, and system aspect. The semantic path therefore returns to the environmental condition that initially motivated the strategy, providing an example of logical closure across environmental, strategic, policy, operational, and behavioral subsystems.

### 5.1. Energy demand ontology design pattern

The energy demand ODP models energy demand as the result of interactions among socio-economic drivers, environmental conditions, behavioral patterns, technological factors, policy measures, and demand-side economic mechanisms. The pattern provides an explicit basis for demand-side analysis within the energy transition by representing not only the factors that influence demand, but also the mechanisms through which consumers and system actors respond to prices, income, relative price changes, and grid conditions.

It refers to the amount of energy required by individuals, households, industries, and societies as a whole to meet their various needs and activities [47]. It represents the total energy consumed over a given period, typically measured in units such as kilowatt-hours (kWh) or joules. Energy demand depends on multiple interrelated factors, including population dynamics [47,100], available technologies [101,102], energy efficiency policies [12,100], weather conditions [47,100,103], behavioral patterns [102], and broader economic conditions [100]. The ODP further specifies the economic dimension by distinguishing

between energy market prices, elasticity measures, income effects, substitution effects, and demand-response processes.

Energy market prices are represented as factors influencing energy demand, while price elasticity and income elasticity specify the responsiveness of demand to changes in prices and consumer income, respectively. Consumer income gives rise to an income effect, which influences energy demand by affecting the purchasing capacity of consumers. Relative price changes trigger a substitution effect, through which consumers may shift demand between alternative energy carriers or technologies. Demand response is represented as a demand-side management process initiated by energy providers or grid operators, enabled by policy instruments and market mechanisms, and activated in response to price signals or grid conditions. Through demand response, consumers participate in the adjustment of demand in order to support objectives such as grid balance and peak demand reduction.

A representative feedback mechanism in the energy demand ODP concerns the interaction between energy demand, grid condition, and demand response. Changes in energy demand may affect grid condition; grid condition may trigger demand response, which in turn modifies energy demand. This forms a closed directed semantic path in which demand-related system conditions can activate corrective demand-side actions that subsequently alter the demand contributing to those conditions.

The pattern also formalizes the relationships among energy demand, influencing factors, demand-side economic mechanisms, and relevant stakeholders (Fig. 6). Key stakeholders include energy providers, policymakers, researchers, grid operators, and consumers. Energy providers and grid operators may initiate demand-response processes; consumers may participate in them, and policymakers and researchers are represented as actors interested in demand dynamics. In this way, the ODP captures both the structural drivers of energy demand and the behavioral, economic, and operational mechanisms through which demand can change during energy transition processes.

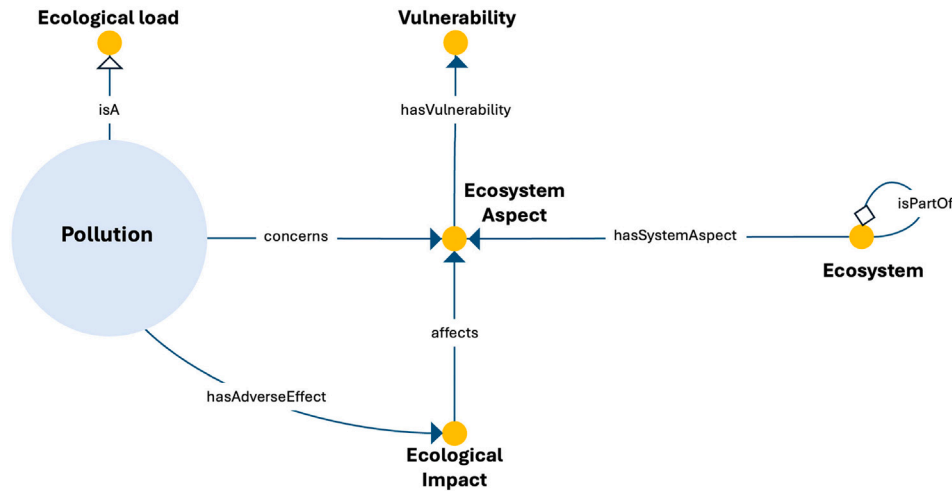


**Fig. 7.** Conceptual representation of the energy pollution ontology design pattern, illustrating pollution as an ecological load and its impacts on interconnected ecosystems.

Source: Authors.

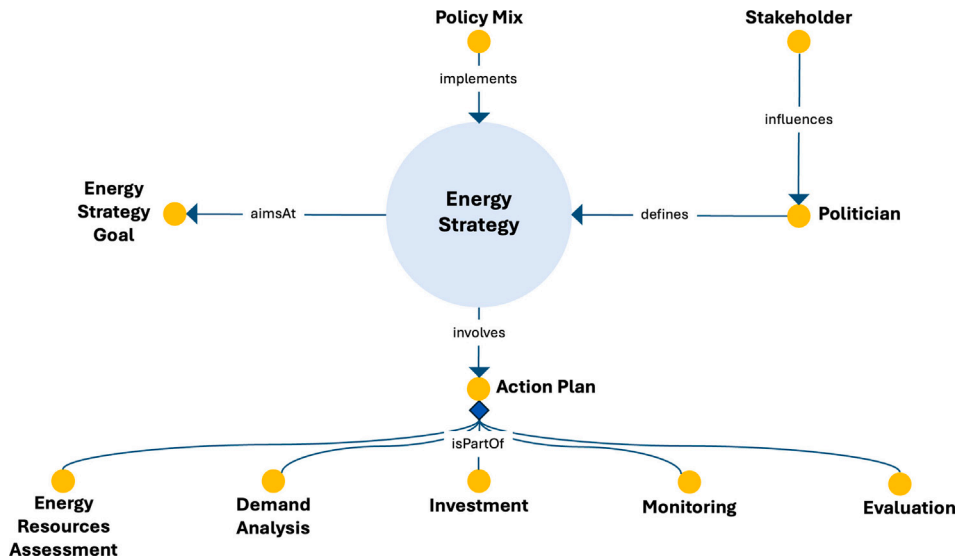


**Fig. 8.** Conceptual representation of the energy strategy ontology design pattern, illustrating the relationships between strategic objectives, policy instruments, stakeholders, and implementation processes.

Source: Authors.

### 5.2. Energy pollution ontology design pattern

The energy pollution ODP models pollution as an environmental pressure within energy systems, capturing its impacts across interconnected ecosystems (Fig. 7). Pollution is conceptualized as the introduction of harmful substances that affect ecological balance and human well-being [104], originating from both anthropogenic and natural processes [105,106].

It formalizes pollution as an ecological load [51,107], linking pressures to ecosystem vulnerabilities and resulting environmental impacts [104,108]. The pattern also reflects the hierarchical and nested structure of ecosystems [109,110], allowing pollution effects to propagate across interconnected environmental subsystems.

### 5.3. Energy strategy definition ontology design pattern

The energy strategy ODP represents how energy strategies are defined and linked to policy instruments, stakeholders, and implementation processes within the energy transition.

The pattern refers to a comprehensive, long-term plan or set of coordinated actions developed by governments, organizations, or other entities to guide decisions on energy production, distribution, consumption, and management [46]. It formalizes the relationships among strategic objectives, policy instruments, and relevant actors (Fig. 8). Energy strategies are characterized by objectives such as the transition towards renewable energy sources or the pursuit of energy security and are operationalized through policy mixes that implement the strategic vision [50]. The pattern further captures the role of policymakers and stakeholders in strategy formulation and its implementation through action plans, including resource assessment, demand analysis, investment planning, and monitoring and evaluation activities [46].

### 5.4. Energy policy ontology design pattern

The energy policy ODP represents how energy policies are defined and implemented in relation to broader energy strategies and their potential consequences within the energy transition.

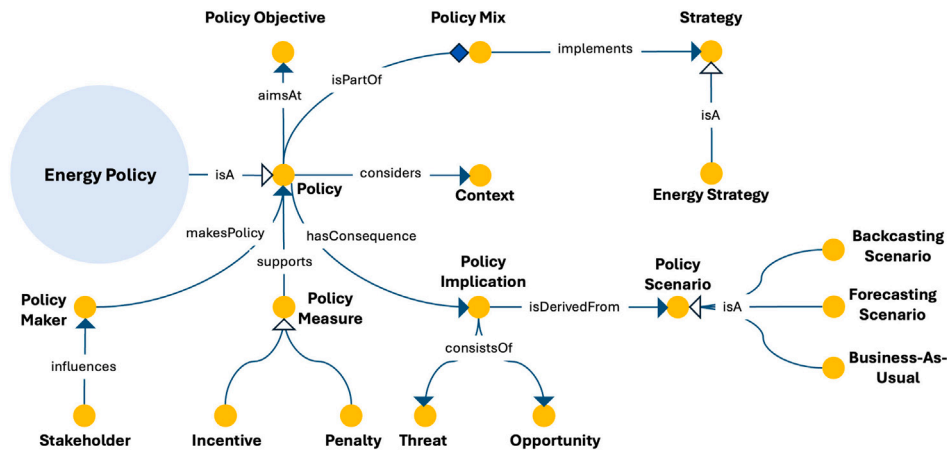


Fig. 9. Conceptual representation of the energy policy ontology design pattern, illustrating policy objectives, contextual factors, implementation measures, and potential consequences.  
Source: Authors.

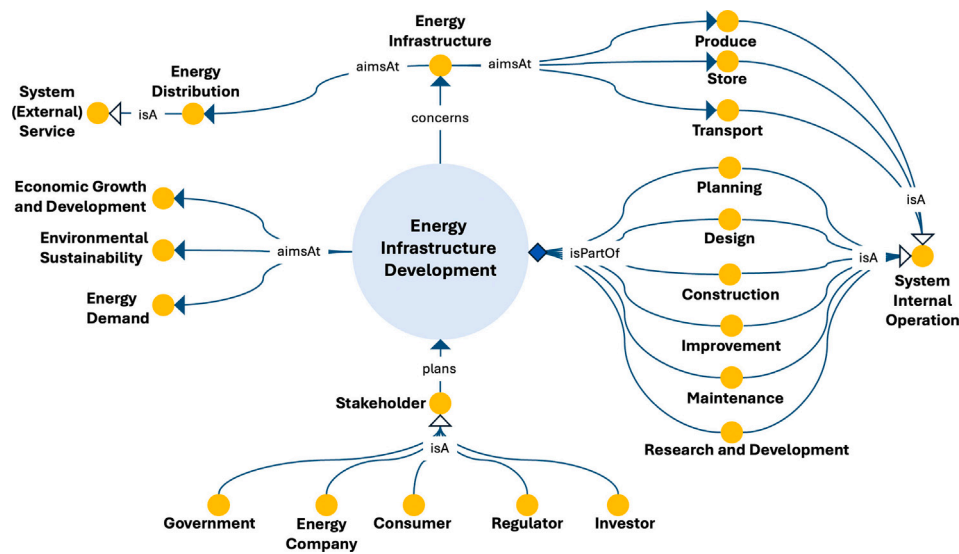


Fig. 10. Conceptual representation of the energy infrastructure development ontology design pattern, illustrating infrastructure assets, development activities, stakeholders, and system objectives.  
Source: Authors.

The pattern refers to a set of regulatory measures addressing energy production, distribution, consumption, and conservation at the national or regional level [111]. It formalizes the relationships between policy objectives, contextual factors, implementation instruments, and outcomes (Fig. 9). Energy policies are characterized by specific objectives, such as increasing the adoption of electric vehicles [50,112,113], and are formulated by policymakers within an institutional context influenced by multiple stakeholders [55,113]. This ODP captures how policies account for economic and geographical factors [114], are embedded in broader policy mixes implementing overarching energy strategies, such as the energy transition or energy security [57,114], and are supported by measures including incentives and penalties [113,114]. It also represents the consequences of energy policies, encompassing opportunities and risks [79,114], which can be assessed through alternative policy scenarios, including backcasting, forecasting, and Business-As-Usual (BAU) scenarios [113–115].

##### 5.5. Energy infrastructure development ontology design pattern

The energy infrastructure development ODP represents how infrastructure development activities relate to energy services, sustainability

objectives, demand requirements, and planning actors within the energy transition.

The pattern refers to the planning, design, construction [116], improvement, maintenance, and research and development of physical systems and facilities enabling the production, transport, distribution, and storage of energy resources [117]. Energy infrastructure development supports economic growth and environmental sustainability by meeting energy demand and is planned by stakeholders such as governments, energy companies, regulators, and investors [118].

It formalizes relationships between infrastructure assets, development activities, objectives, and stakeholders (Fig. 10). Then, it captures how development concerns specific infrastructure entities and core energy functions, distinguishes development activities and operational functions from energy distribution as an external service, and represents the contribution of infrastructure development to meeting energy demand, sustainability goals, and broader economic development [117].

##### 5.6. Policy acceptance ontology design pattern

The policy acceptance ODP represents how the acceptance of energy policies arises from the interaction between individual and collective

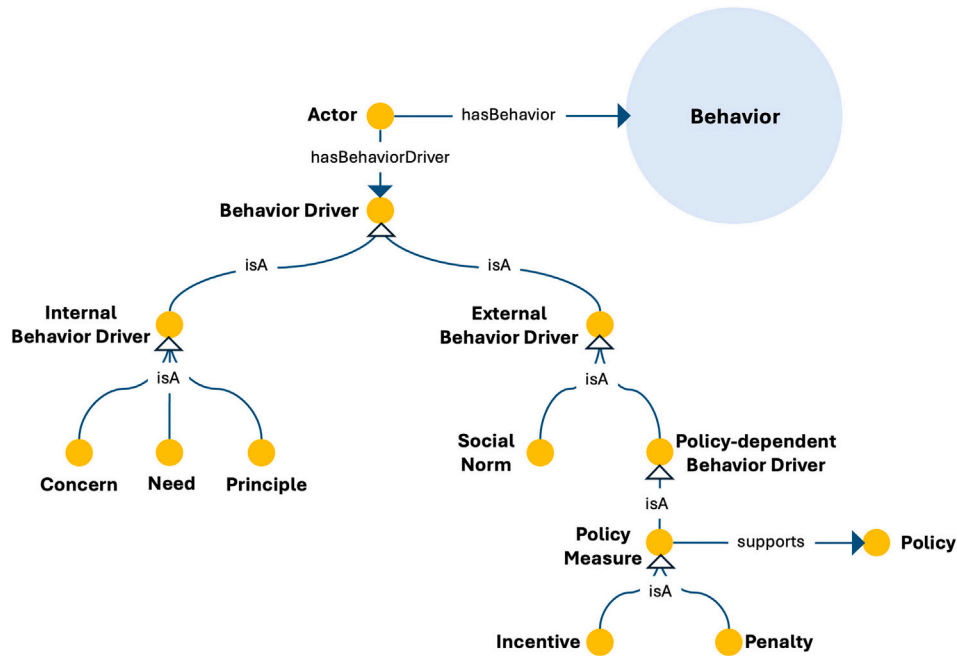


Fig. 11. Conceptual representation of the policy acceptance ontology design pattern, illustrating the relationships between actors, behavioral drivers, and policy support measures.

Source: Authors.

behaviors, their drivers, and policy support measures within the energy transition.

The pattern refers to the degree to which individuals, social groups, or stakeholders affected by a policy or governmental decision support or comply with that policy [119–121]. Policy acceptance reflects levels of approval, trust, and willingness to cooperate with implementation and is a critical factor for policy effectiveness [121,122], while low acceptance can hinder implementation and limit intended outcomes [60,123].

It formalizes the relationships between actors, behaviors, and drivers influencing acceptance (Fig. 11). Then, it captures how actors' behavior is shaped by internal and external drivers [120,124–126], including needs, principles, and concerns such as awareness of energy issues and climate change [125,127], as well as social norms and policy support measures, such as incentives and penalties, that can facilitate or constrain acceptance and compliance [126,128,129].

### 5.7. Energy saving ontology design pattern

The energy saving ODP represents energy-saving behaviors, their effects on energy consumption, and the role of user satisfaction within the energy transition.

The pattern refers to reducing energy consumption or improving efficiency while delivering the same level of service and maintaining user satisfaction [130–133]. It formalizes relationships between energy end users, their behaviors, and the outcomes of energy-saving actions (Fig. 12). Energy saving is modeled as a user behavior leading to reduced energy consumption [61], with benefits including lower energy costs, enhanced energy security, environmental gains, and contributions to sustainable development. User satisfaction is explicitly represented as a condition for the persistence and effectiveness of energy-saving behaviors and is influenced by behavioral drivers, linking energy usage and energy consumption to user actions.

### 5.8. Energy market ontology design pattern

The energy market ODP represents the interaction of market participants trading energy commodities, including the institutional, economic, technological, and policy-related mechanisms that shape prices, supply, demand, externalities, and market outcomes [50,134].

The energy market ODP models the energy market as an institutional and economic arrangement in which energy market participants trade energy commodities under specific market structures and market mechanisms. The pattern also represents how energy markets coordinate energy supply and energy demand, while energy market prices both influence and are influenced by supply and demand dynamics [76,135].

The ODP further specifies the economic mechanisms underlying price formation. Market mechanisms, including pricing mechanisms, enable energy exchange and determine energy market prices, while energy market structures affect market power, constrain market participants, and influence market prices [135]. System costs, energy supply, energy demand, and policy instruments are also represented as factors affecting energy market prices [50,58]. In this way, the pattern makes explicit that prices are not isolated variables, but are shaped by market organization, cost structures, policy intervention, and supply–demand interactions.

The pattern also represents externalities, social costs, and market failures. Energy markets may generate externalities, including environmental externalities, which contribute to market failures and social costs [136]. Energy market prices may therefore fail to reflect social costs. Policy instruments are represented as mechanisms that can address market failures and affect energy markets and energy market prices [57,58]. Carbon pricing, subsidies, and taxes are represented as specific policy instruments; carbon pricing internalizes environmental externalities, while subsidies may support energy technologies [58].

The ODP connects market dynamics to technology costs and investment-related processes. Energy technologies are associated with cost indicators such as the levelized cost of electricity (LCOE), as well as capital and operating costs [137]. Since technology-level generation costs do not capture all system-level effects associated with variable renewable generation, the pattern also distinguishes integration costs and broader system costs [138,139]. LCOE is calculated using the discount rate and influences technology competitiveness. Investment appraisal uses the discount rate, evaluates energy technologies, and assesses technology competitiveness, which in turn influences technology adoption [80,140]. These economic concepts are represented semantically rather than computationally. ESO specifies their meaning and relationships but does not calculate numerical values such as LCOE, discount rates,

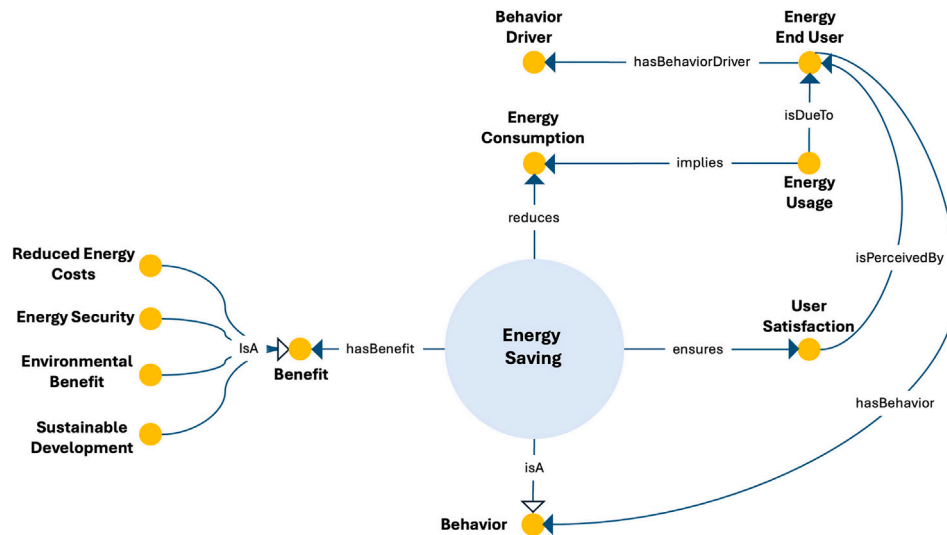


**Fig. 12.** Conceptual representation of the energy saving ontology design pattern, illustrating energy-saving behaviors, their benefits, and the role of user satisfaction. Source: Authors.

elasticities, or system costs. Their numerical estimation relies on external models, datasets, and analytical procedures connected to the ontology. Technology adoption affects energy supply and demand and, through technology competitiveness, also affects energy market dynamics [140]. Climate change concern and geopolitical factors are represented as broader contextual drivers: the former motivates policy instruments, while the latter affects energy supply [113,141].

Within the energy market ODP, stranded asset risk is represented through a simplified structure in which policy instruments, energy market prices, and technology competitiveness affect stranded asset risk, which concerns an asset. Stranded asset risk is modeled as a specialization of risk, whereas stranded asset is a specialization of asset. A more detailed representation can be obtained by reusing ESO's risk ODP, which provides explicit structures for hazards, vulnerabilities, critical events, and affected system aspects.

The ontology design patterns shown in these figures are modular views centered on selected domain concepts. They are therefore not intended to display every possible path in the integrated ontology. When the patterns are connected, their relations can form longer cross-subsystem paths and feedback loops. In the energy market ODP, one such loop is explicitly highlighted to demonstrate how feedback is represented in ESO.

Fig. 13 provides an illustrative example of such logical closure. Climate change concerns motivate a policy instrument, which affects the energy market; market activity may generate an environmental externality, which in turn informs a subsequent policy instrument. The feedback is therefore logically closed in the integrated ontology through the sequence of semantic relations, even though the graphical representation highlights only the relevant modular view. The cross-subsystem feedback path is shown in bold in Fig. 13. Technology adoption also affects energy supply and energy demand, contributing to market outcomes and to the associated social and environmental consequences. The path therefore returns to the policy subsystem and represents feedback in which the consequences of prior policy, market, and technology developments shape subsequent intervention.

An illustrative real-world example is the evolution of agrivoltaic policy. Climate-policy objectives and renewable-energy support stimulated photovoltaic deployment. The expansion of ground-mounted photovoltaic installations also raised concerns about land-use competition and the continuity of agricultural production. These consequences informed new instruments promoting systems in which electricity generation and agriculture coexist. Italy's Ministerial Decree No. 436/2023

[142], for example, introduced dedicated incentives for advanced agrivoltaic systems while requiring the continuation of agricultural activity. The example shows how an environmental policy concern can initiate market and technological change, whose externalities subsequently inform a new policy instrument.

## 6. Ontology verification and application for energy system analysis

The assessment of ESO is conducted through complementary requirements-based and application-oriented perspectives. First, ESO is verified against the competency questions established during the requirements-specification phase, examining whether its formal structure supports the analytical questions that the ontology was designed to address and their implementation through SPARQL. This activity is intended as requirements-based verification rather than as an independent external validation. Second, ESO's potential to support semantic interoperability is investigated through an illustrative alignment with CIM100, a version of the Common Information Model used for electricity-system information exchange within the CGMES ecosystem, thereby showing how elements from an established industrial information model can be represented through reusable ESO structures. Third, the practical applicability of ESO is illustrated through its prior use in a study of the energy transition research community, where it supported corpus filtering, thematic classification, and the construction of a structured dataset for multidisciplinary analysis [143]. Finally, the main limitations of the current ontology and the requirements for its further operationalization and external validation are discussed.

### 6.1. Requirements-based verification through competency questions and semantic querying

Competency questions are commonly used in ontology engineering to specify the informational requirements that an ontology is expected to satisfy and subsequently to verify whether the resulting conceptualization supports those requirements [144]. Accordingly, they should be understood as requirements defined during ontology development rather than as an independent external test formulated after completion of the ontology.

In the development of ESO, ontology engineers and domain experts performed distinct but complementary roles. The ontology engineers contributed expertise in conceptualization, formalization, and ontology modeling techniques, whereas the domain experts contributed the

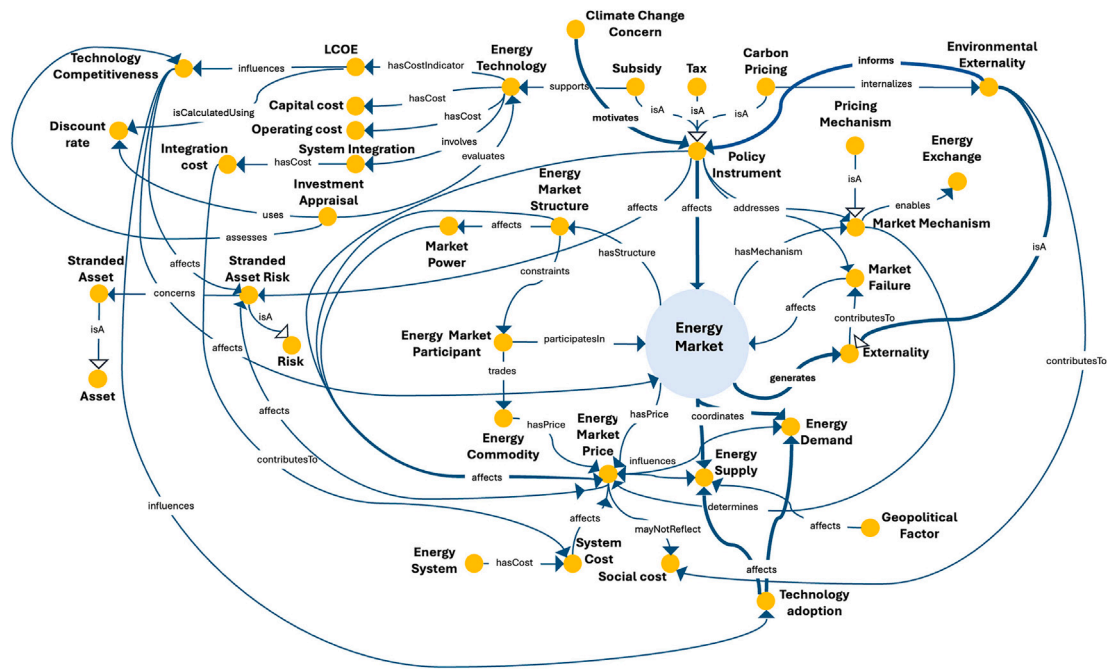


**Fig. 13.** Energy market ontology design pattern. Bold relations highlight an illustrative cross-subsystem feedback path connecting environmental concern, policy intervention, market coordination, technology adoption, environmental externalities and subsequent policy intervention. The remaining relations are shown with standard line weight.

Source: Authors.

substantive knowledge required to specify the relevant informational requirements of the energy transition domain. During the requirements-specification phase, the domain experts formulated 50 competency questions expressing the types of questions that ESO should be able to represent and support. These competency questions intentionally informed the subsequent ontology engineering activities and are used here to verify whether the resulting ontology satisfies those initial requirements. Accordingly, successful answering of the competency questions demonstrates consistency with the requirements defined during ontology development, but should not be interpreted as independent external validation of ESO. Examples of such questions include: (i) *which factors influence energy demand in a given region*, (ii) *which policies support the adoption of renewable energy technologies*, (iii) *which roles different stakeholders play in energy markets*, (iv) *how climate conditions influence renewable energy generation*, and (v) *which strategies are associated with improving energy security*. ESO is explicitly designed to address these competency questions by integrating concepts and relationships across multiple dimensions of the energy system, including demand, policy, market actors, environmental conditions, and strategic planning. As illustrated in Table 4, the ontology captures how energy demand is influenced by contextual factors such as region, how policies support the adoption of renewable technologies, and how different actors assume specific roles within energy markets. Furthermore, ESO enables the representation of the influence of climate conditions on renewable energy generation, as well as the role of strategies in enhancing energy security. These examples demonstrate the ontology's ability to model interdependencies across environmental, socio-economic, and governance dimensions. Overall, the correspondence between the competency questions and the ontology elements demonstrates the consistency between the requirements established during ontology development and the resulting ESO representation, providing requirements-based evidence that the ontology fulfills its intended design requirements.

The competency questions were not the sole source used to determine the conceptual content of ESO. As described in [Section 4](#), the elicitation process also adopted a bottom-up, literature-driven approach. A total of 15,367 Scopus-indexed publications on energy transition for

Table 4

Exemplary competency questions and corresponding ESO elements (i.e., classes and properties).

| Competency question                                                   | ESO elements                                                                                  |
|-----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| What factors influence energy demand in a given region?               | <b>Classes:</b> energy demand, factor, region<br><b>Properties:</b> isInfluencedBy, occursIn  |
| Which policies support the adoption of renewable energy technologies? | <b>Classes:</b> policy, renewable technology<br><b>Properties:</b> supports                   |
| What roles do different stakeholders play in energy markets?          | <b>Classes:</b> energy market participant, energy market<br><b>Properties:</b> participatesIn |
| How do climate conditions influence renewable energy generation?      | <b>Classes:</b> climate condition, renewable generation<br><b>Properties:</b> influences      |
| Which strategies are associated with improving energy security?       | <b>Classes:</b> strategy, energy security<br><b>Properties:</b> improves                      |

Source: Authors.

which keywords were available were analyzed to identify candidate domain terminology. The extracted terminology was subsequently reviewed and validated by domain experts before being incorporated into the ontology-development process. ESO's conceptualization therefore combines evidence derived from a large scientific corpus, domain expertise, and ontology engineering methods. This procedure reduces the risk that the ontology merely reproduces the development team's prior assumptions, although it does not constitute independent external validation.

To further assess its practical relevance, we illustrate how ESO supports query-based exploration of the energy transition domain. Fig. 14 shows a query expressed in SPARQL (SPARQL Protocol and RDF Query Language) that retrieves the set of factors influencing energy demand, together with their conceptual classification. The results of the query highlight the heterogeneous nature of the factors influencing energy demand, spanning behavioral, technological, policy, and environmental dimensions. In particular, the ontology identifies elements such as behavior, energy efficiency policy, technology, and weather as relevant

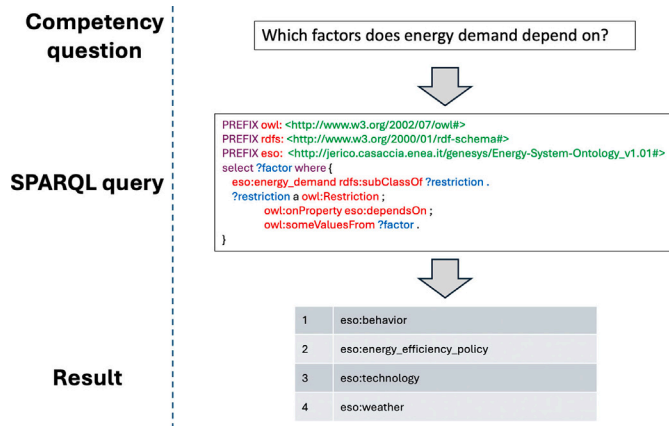


**Fig. 14.** Example of competency question translated into SPARQL and corresponding query results retrieved from ESO.  
Source: Authors.

drivers. This outcome reflects the multidimensional structure of ESO, where energy demand is not modeled as a purely technical variable, but as the result of interacting socio-technical and environmental processes. By explicitly linking these diverse factors within a unified semantic framework, ESO enables a more integrated analysis of demand dynamics, supporting the identification of cross-domain interactions that are often treated separately in traditional energy models. This integrative capability, already highlighted in the comparison with existing ontologies (see Table 1), is reflected in the query results, which span multiple heterogeneous dimensions of the energy system. The query illustrates how the knowledge formalized in ESO can be accessed programmatically to answer a defined analytical question. SPARQL querying therefore represents one of the fundamental mechanisms through which ontology-based applications can retrieve, combine, and organize knowledge for energy transition assessments.

From an application perspective, this capability supports researchers and policymakers in exploring how different types of interventions, such as technological innovation, behavioral change, or policy measures, jointly influence energy demand, thereby facilitating more comprehensive and system-oriented assessments of energy transition pathways.

While the example focuses on energy demand, the same querying approach can be applied to other core dimensions of the ontology, such as policy, technology adoption, or energy security. This demonstrates that ESO supports a consistent and reusable mechanism for addressing a broad class of analytical questions, rather than a single isolated case. In this sense, the competency questions are not only verified individually, but also illustrate how the same querying mechanism can be reused across a broader class of ontology requirements.

The ability to explicitly connect heterogeneous factors influencing energy demand has direct implications for energy system analysis. In particular, ESO enables the integration of variables that are typically modeled separately, such as socio-economic conditions, policy interventions, and environmental drivers. This supports more comprehensive analytical workflows, including scenario analysis, policy evaluation, and cross-sectoral impact assessment. By structuring these relationships semantically, the ontology facilitates the comparison of results across studies and improves transparency in how different assumptions and drivers are represented. For example, a policymaker could use ESO to identify and compare the relative influence of behavioral, technological, and regulatory factors on energy demand in a given context, supporting the design of more targeted and effective interventions.

## 6.2. Illustrative semantic alignment with CIM100

To provide a concrete illustration of ESO's potential role as a semantic-interoperability layer, we performed an illustrative alignment

**Table 5**  
Illustrative CIM100–ESO mapping card for AirCompressor.

| Field                        | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CIM element                  | AirCompressor                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| CIM element type             | Class                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| CIM package                  | IEC61970::Base::Generation::Production                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| CIM definition               | Combustion turbine air compressor which is an integral part of a compressed-air energy-storage plant.                                                                                                                                                                                                                                                                                                                                                                    |
| ESO representation           | physical infrastructure + relatedTo some compressed air energy storage + hasQuality some rated power                                                                                                                                                                                                                                                                                                                                                                     |
| Structural mapping type      | Class-to-pattern                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Semantic correspondence      | Broader and composite                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Mapping direction            | CIM → ESO                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Rationale                    | The CIM class denotes a physical compressor that is an integral component of a compressed-air energy-storage plant. ESO does not contain a dedicated air compressor class, but the concept can be reconstructed through reusable ontology structures. Its ontological category is represented by physical infrastructure, its functional context by a relation to compressed air energy storage, and its rated-power characteristic by the quantitative-quality pattern. |
| Residual semantic difference | Physical infrastructure is broader than AirCompressor. Moreover, relatedTo does not express the specific component relation conveyed by the CIM definition. The pattern also does not reproduce compressor-specific construction and operating characteristics.                                                                                                                                                                                                          |

Source: Authors.

with the Common Information Model (CIM). The analysis uses the CIM100\_CGMES31v01\_501-20v02\_NC21v52\_MM10v01.eap Enterprise Architect model distributed by the European Network of Transmission System Operators for Electricity (ENTSO-E) in connection with CGMES 3.0 [145]. The artefact contains the CIM 100 UML (Unified Modeling Language) model used in the CGMES ecosystem and provides a machine-readable representation of classes, attributes, associations, and specialization relationships used in electricity-system information exchange. Its established use for interoperability among power-system applications makes it a suitable external representation against which to examine ESO's semantic-alignment capability.

The example is intentionally limited and should not be interpreted as a complete mapping between ESO and CIM100 or between ESO and the complete set of CGMES exchange profiles. We selected elements from the IEC61970::Base::Generation::Production package, which contains representations of generation and storage equipment together with engineering attributes, operational characteristics, fuels, schedules, and performance curves. The objective is to examine whether a specialized external representation can be reconstructed through reusable ESO structures rather than to reproduce the complete CIM schema.

The selected example concerns the CIM class AirCompressor and its quantitative attribute airCompressorRating. CIM defines AirCompressor as a combustion-turbine air compressor that is an integral part of a compressed-air energy-storage plant. ESO does not contain a dedicated air compressor class. Nevertheless, its semantics can be represented compositionally: its ontological nature is captured by physical infrastructure, its functional context by a relation to compressed air energy storage, and its rated active power through the quantitative-quality pattern described in Section 4.2.4.

The example illustrates two complementary forms of semantic alignment. At the class level (see Table 5), the mapping is broader and composite rather than equivalent: AirCompressor is more specific than physical infrastructure, and its meaning is reconstructed by combining an ontological category, a functional context, and a quantitative quality. At the attribute level (see Table 6), a scalar UML attribute is transformed into an explicit ontology structure that distinguishes the quality from the information specifying its magnitude. The absence of a terminologically identical ESO class therefore does not necessarily prevent semantic representation, provided that the meaning of the external element can be reconstructed through reusable ESO structures.

**Table 6**  
Illustrative CIM100–ESO mapping card for the `AirCompressor.airCompressorRating` attribute.

| Field                        | Description                                                                                                                                                                                                                                                                                                                                                    |
|------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CIM element                  | <code>AirCompressor.airCompressorRating</code>                                                                                                                                                                                                                                                                                                                 |
| CIM element type             | Attribute                                                                                                                                                                                                                                                                                                                                                      |
| CIM package                  | IEC61970::Base::Generation::Production                                                                                                                                                                                                                                                                                                                         |
| CIM meaning                  | Rated active power of the air compressor.                                                                                                                                                                                                                                                                                                                      |
| ESO representation           | rated power + hasQuantityValue some quantity value, where quantity value carries a decimal numericValue and a string-valued measurementUnit.                                                                                                                                                                                                                   |
| Structural mapping type      | Attribute-to-quantitative-quality pattern                                                                                                                                                                                                                                                                                                                      |
| Semantic correspondence      | Composite                                                                                                                                                                                                                                                                                                                                                      |
| Mapping direction            | CIM → ESO                                                                                                                                                                                                                                                                                                                                                      |
| Rationale                    | The CIM attribute expresses a quantitative characteristic of the compressor. In ESO, the characteristic is represented by rated power, modeled as a specialization of quantitative quality. Its magnitude is represented separately through a quantity value, which carries the numerical component through numericValue and the unit through measurementUnit. |
| Residual semantic difference | Because measurementUnit is represented as an <code>xsd:string</code> , ESO records the unit expression but does not currently infer dimensional compatibility, normalize equivalent units, or perform unit conversions automatically.                                                                                                                          |

Source: Authors.

This distinction is central to the intended meaning of ESO as a semantic bridge. Semantic interoperability does not require asserting one-to-one equivalences where the underlying representations differ. Rather, the alignment should make explicit which concepts correspond directly, which are broader or narrower, which require a combination of ontology elements, and which aspects remain outside the current representation.

The alignment also provided a practical test of the reusability of ESO's modeling structures. It showed that the asset and functional context of `AirCompressor` could be represented compositionally, while quantitative engineering attributes required a uniform way of relating qualities to numerical values and measurement units. Rather than introducing a property specific to `airCompressorRating`, this recurring requirement was generalized into the quantitative-quality pattern introduced in Section 4.2.4. The same structure can be specialized for other energy-system quantities, including storage capacity, stored energy, generator ratings, conversion efficiency, reservoir levels, fuel consumption, and emission quantities. This illustrates the intended extensibility of ESO's domain upper ontology: additional knowledge is incorporated by specializing reusable structures rather than by pre-encoding every possible domain attribute.

The CIM100 worked example provides evidence of ESO's potential to act as a semantic-interoperability layer between heterogeneous representations. It does not constitute a complete mapping to CIM100 or CGMES, nor does it imply that ESO already provides mappings to all energy-system models and standards. Rather, it demonstrates how external information structures can be aligned with ESO through direct and compositional semantic correspondences while preserving explicit information about residual differences.

### 6.3. Application of ESO to the energy transition research community

ESO has already been applied in a study of the scientific knowledge community working on energy systems and the energy transition [143]. Starting from 17,591 publications retrieved from Scopus, ESO concept labels were used to filter the corpus, retaining 10,130 domain-relevant papers. After author-data processing, the final dataset comprised 9097 publications and 27,363 authors. ESO further supported the classification of the publications into the environment, strategy, policy, behavior, and operations subsystems through a relevance function

combining publication impact, keyword occurrence, and expert-derived thematic weights. The resulting scientific communities were analyzed through bibliometric, semantic, statistical, and social-network indicators to assess gender differences in participation, collaboration, thematic orientation, influence, creativity, and scientific success. This application demonstrates that ESO can operate as a semantic resource for corpus delimitation, thematic classification, and the construction of structured datasets for multidisciplinary assessment.

Importantly, this application differs from the requirements-based verification and the CIM100 alignment presented above. Rather than assessing whether ESO satisfies predefined ontology requirements or can be aligned with an external information model, it illustrates the operational use of the ontology as a semantic resource within an empirical research workflow. It therefore provides complementary evidence of ESO's practical applicability, although it should not be interpreted as independent external validation of the ontology.

### 6.4. Limitations and future research

From a qualitative perspective, ESO exhibits several desirable characteristics. It ensures semantic coherence by grounding domain concepts in a well-established foundational ontology (BFO), promotes modularity through ontology design patterns, and supports interoperability by aligning with existing ontologies such as the Open Energy Ontology and standard W3C vocabularies. Moreover, as mentioned, ESO is conceived as a living entity, designed to evolve as new knowledge and requirements emerge and, in line with the open-world assumption, the absence of certain relationships should not be interpreted as their invalidity, but rather as an indication that they have not yet been formalized.

Taken together, the requirements-based verification, the CIM100 alignment, and the prior application illustrate complementary aspects of ESO's current capabilities. By enabling the explicit modeling of complex interdependencies and supporting both direct and multi-step queries, ESO contributes to improving the transparency, consistency, and reusability of knowledge in interdisciplinary energy research while helping to bridge the gap between conceptual modeling and practical energy analysis.

ESO provides a semantic foundation for the development of energy transition assessment applications rather than constituting a complete assessment model in itself. The ontology formalizes the concepts and relationships required to represent the technological, economic, institutional, social, and environmental dimensions of energy transition, thereby enabling heterogeneous information to be organized within a shared and machine-interpretable structure. Its operationalization in a specific assessment context requires an additional application layer, including the mapping of ontological concepts to relevant indicators and data sources, the population of the ontology with data concerning territories, technologies, actors, policies, infrastructures, or scenarios, the definition of SPARQL queries, inference rules, or analytical procedures, the development of user-oriented interfaces, and the validation of the resulting application against empirical cases. The particular implementation therefore depends on the purpose, scale, datasets, indicators, and stakeholders involved in the assessment.

At the present stage, developing ESO-based applications requires collaboration between ontology engineers and domain experts. Ontology engineers are responsible for implementing mappings, queries, reasoning mechanisms, and semantic services, while domain experts define the relevant indicators, data requirements, assessment criteria, and interpretation of the results. This does not imply that final users must be familiar with ontology languages or semantic query languages, since dedicated interfaces and software services can conceal the underlying technical complexity and make ESO-based functionalities accessible to analysts, policymakers, and other energy transition stakeholders.

Although the application described in Section 6.3 provides initial evidence of ESO's operational applicability, it was based on scientific publications rather than on case-specific empirical energy-system data.

Further research is therefore needed to evaluate ESO in relation to specific territories, technologies, infrastructures, organizations, and policy interventions. Such applications will require the ontology to be populated with case-specific instances, its concepts to be linked to measurable indicators and external data sources, and dedicated queries, inference rules, and analytical interfaces to be implemented. Future work will thus extend the existing corpus-based application towards territorial, technological, and policy assessment cases. The CIM100 alignment presented in this study should likewise be interpreted as an illustrative interoperability case rather than as a comprehensive mapping to an industrial information model. Extending the alignment to additional CIM packages, exchange profiles, energy-system models, and domain standards would require dedicated mapping and validation activities, since each external representation adopts its own scope, granularity, constraints, and modeling assumptions. Future work will therefore investigate systematic alignment procedures and machine-actionable transformations between ESO and selected external semantic and modeling resources. The temporal and network-topology extensions introduced in ESO are intentionally lightweight. They provide the semantic distinctions required to relate energy-domain concepts to different temporal scales, network locations, market zones, capacities, and constraints, but are not intended to reproduce the detailed representations required for operational power-system simulation. Applications requiring terminal-level connectivity, switching states, detailed electrical parameters, or dynamically derived network configurations may further specialize ESO or align it with dedicated electricity-network standards such as CIM/CGMES.

The evaluation presented in this study also has methodological limitations. The competency-question assessment constitutes requirements-based verification rather than independent external validation, because the questions were formulated by domain experts participating in the broader ontology-development process and intentionally informed the content of ESO. However, the ontology-development process was not limited to the six experts involved in the initial concept-to-subsystem assessment: additional domain experts and project partners were subsequently involved in reviewing and refining the ontology and its conceptual content. This broader review process provided an additional layer of expert scrutiny beyond the initial elicitation stage. Likewise, the comparative coverage assessment reported in Table 1 was conducted by the authors using the qualitative rubric described in Section 2. Although the same criteria were applied consistently to all considered ontologies, the resulting classifications retain an element of subjective interpretation and may therefore be affected by author-related bias. Future validation should include a blind external expert evaluation in which other assessors, external to the ESO development process and not involved in the previous expert review activities, independently evaluate the ontology using predefined criteria and without access to the authors' original assessment outcomes. Such an evaluation would provide a stronger basis for assessing the robustness, usability, and representational adequacy of ESO independently of the development team.

Finally, although formal ontologies and knowledge graphs have been investigated as grounding resources for LLM-based systems, the present study does not evaluate ESO in such a setting. No comparison between ungrounded and ESO-grounded LLM configurations has been performed, and the present results therefore do not demonstrate improvements in terminological consistency, factual grounding, or reasoning attributable to ESO. Evaluating ESO as a domain-specific grounding resource for LLM-based energy applications, for example through competency-question answering and ontology-constrained reasoning tasks, represents a direction for future research.

## 7. Conclusion

This paper presents the Energy System Ontology as a formal and extensible conceptual framework designed to support the systematic organization and synthesis of knowledge related to energy systems and the energy transition. In response to the growing diversity of analytical

approaches, terminologies, and disciplinary perspectives in energy research, ESO provides a structured semantic reference that enables consistent representation of heterogeneous concepts across technological, economic, policy, behavioral, and environmental domains.

ESO is grounded in a systematic, multidisciplinary review of the energy transition literature and implemented using established ontology engineering and design science principles. By formalizing core concepts and relationships into ontology design patterns, the ontology captures recurring structures across energy systems research while preserving disciplinary distinctions and supporting semantic alignment across heterogeneous datasets and model representations, interoperability among datasets and models, and integrative analyses.

Rather than offering predictive capabilities or prescriptive policy guidance, ESO is intended as reusable conceptual infrastructure aimed at improving clarity, coherence, and comparability in energy systems research. By making explicit the conceptual assumptions underlying energy transition analyses, ESO provides a foundation for future review-based and model-oriented studies and can be extended as new technologies, policies, and analytical perspectives emerge. The illustrative alignment with CIM100 further demonstrates how this extensibility can support semantic interoperability with an established industry information model. The worked example shows that specialized external elements need not have one-to-one counterparts in ESO: their semantics can also be represented compositionally by specializing and combining reusable ontology structures. The alignment additionally provides a practical test of the reusability of the ontology's modeling architecture, leading to the generalization of a reusable quantitative-quality pattern for representing numerical values and measurement units associated with energy-system qualities.

The practical applicability of ESO was already demonstrated in a separate study, where it was used to delimit and structure a large corpus of scientific publications on the energy transition and to organize the resulting dataset according to the five subsystems represented in the ontology [143]. This application provides evidence of ESO's use as an operational semantic resource for corpus filtering, thematic classification, and the preparation of structured data for multidimensional analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

The ESO ontology files, Ontology Design Pattern diagrams, SPARQL query examples, keyword-frequency data, and expert annotation materials are publicly available at <https://antoniodenicola.github.io/eso-odp-site/>.

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